Aggressive Growth in the Use of Bio-derived Energy and Products in the United States by 2010

Prose Summary, Final Report

Notice:

This Text Summary is the companion to the more detailed report and data volume. For a more complete description of issues and analyses, the complete report must be considered.

Report to
U.S. Department of Energy and
U.S. Department of Agriculture

Executive Summary

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Prose Summary

Guide to this Summary

This document is a prose companion document to our main presentation-style report and data volume. The reader is encouraged to refer to the main report and data volume for a more detailed description of the assumptions, the analysis, and the conclusions.

This document is divided into two pieces, the prose summary of our results, and a summary appendix, with key accompanying information. The summary in turn is divided into ten chapters (aside from this guide). First we present an executive summary of our findings in the “Abstract of Key Findings”. Next, we explain the purpose of the study underlying this report in the “Background and Objectives”. The “Scope, Approach and Study Limitations” section describes how we carried out the study, where the boundaries for the study were, and provides guidelines on how to use and not to use the study. The “Baseline Biomass Use” section then describes the current situation, against which potential increases in biomass use for energy and products, is mentioned. Before analyzing the specific approaches available, we investigate the potential sources of biomass for conversion into energy and products in “Biomass Feedstock Availability and Environmental Impacts”. Then, we describe the options available to increase the use of biomass and the selection we made for detailed analysis in “Options for Growth”. Based on these options, we then analyze how biomass use would grow without any new support instruments, and how biomass energy and product use would grow at the maximum rate in our “Scenario Analysis”. Issues that could hinder the growth of biomass use are discussed in “Barriers to Rapid Growth of Biomass-Based Energy and Products”. Finally, we discuss potential actions the government could take to accelerate the adoption of biomass-based energy and products in “Policy Options” and summarize our findings in the “Conclusions”.

Abstract of Key Findings

The purpose of this report was to identify options that could lead to a significant increase in the use of biomass-based energy and products in the U.S. by the year 2010. A second purpose was to evaluate to what extent these options could benefit the U.S. in terms of environmental impact, rural economic development, U.S. balance of payments, U.S. energy security, and the competitiveness of U.S. industry as they relate to the use of energy and products. The report is the result of a yearlong study carried out by Arthur D. Little for the U.S. Department of Energy (USDOE) based on existing and publicly available information. To ensure an accurate understanding of the results presented here, and to allow the reader to put them in perspective with respect to other studies, we strongly encourage the reader to look at the scope and limitations sections in this prose summary.

Our analysis indicates that with sufficient investment and government support, significant increases in the use of biomass-derived energy and products in the United States could be achieved by year 2010. However, doubling or tripling biomass utilization should realistically not be expected to happen until after 2015.

Our overall conclusion is supported by the key findings presented below:

Biomass Resources

First, the rich land resources of the United States could physically provide sufficient biomass feedstock to satisfy even a tripling of current biomass-derived energy and product production[1]; based on resources that are currently not captured for economic use.[2] However, ratcheting up biomass use to such levels within the next ten years would require considerable attention from policymakers. Such increases would likely lead to feedstock prices that exceed $20/dry ton at the farm-gate (an energy value of approximately $1.1/GJ; $1.2/million BTU using 17.5 GJ/dry ton heating value)[3]. Given process efficiencies and realistic cost goals for biomass conversion processes, costs in

[1] The definition of biomass-derived energy and products for this study includes power production for the pulp & paper industry. Also included are biomass-derived fuels for transportation applications and industrial products such as specialty and commodity chemicals. Excluded from the scope of the study are pulp & paper, lumber products, textiles, foods and food ingredients, and pharmaceutical production.

2 Available biomass is defined as a biomass resource that is currently or potentially collectable and not currently used as energy or any beneficial use and is potentially usable (meaning that it is not contaminated or commingled so as to be unsuitable as a feedstock). Biomass resources for this study included agricultural crop residues (e.g. corn stover, wheat straw, cotton stalks, rice straw), forest residues, primary mill residues, organic fraction of municipal solid waste, urban tree residues, construction & demolition wood, gaseous biomass (e.g. landfill gas, digester gas, sewage gas), sludge (e.g. manure and bio-solids) and potential energy crops (e.g. switchgrass, hybrid poplar and willow).

[3] The biomass sources with the highest potential in the 0 - 40 $/dry ton farm-gate price range are: corn stover (Great Lakes region: Minnesota, Iowa, Wisconsin, Illinois, Indiana, Ohio and Michigan); organic municipal solid waste (Northeast: New England, New York, Pennsylvania, New Jersey, and Delaware); forest residues (Northwest: Washington, Oregon, Idaho, and Montana) and switchgrass (Southeast and West regions: all other states). Hawaii and Alaska were not addressed in this analysis.

excess of $20/dry ton farm-gate represent a significant added challenge in achieving cost-competitiveness of biomass-derived energy and products in their markets.

Options for Increased Biomass Use

Options exist in each category to support considerable near-term growth for biomass utilization (see Figure 1). Together with additional options under development, there is the potential to further expand biomass use in the longer term[4]. The accumulated potential of these options by 2010 was estimated based on a business as usual scenario (e.g. no new incentives, no major changes in drivers), and an aggressive growth scenario (e.g. sufficient incentives to approach what is technically possible). These estimates are shown in Figure 1.

For each sector (e.g. power, transportation fuels, industrial products) a baseline of biomass use was defined using 1998 data.

- Baseline: Current uses and nominal growth in current uses resulting from economic growth.
- Business as Usual (BAU): Baseline activity and baseline growth. Additional growth above baseline from new uses based on current environment.
- Aggressive: Baseline activity and baseline growth. Additional growth above baseline from new uses based on maximum market penetration scenarios.

[4] In this context, near-term means having significant impact before 2010, while long-term means with potentially significant impact in the 2010 – 2020 timeframe.

Figure 1: Promising Technology Options to Dramatically Increase Biomass Utilization by 2010

Application Category	Examples of Technologies	Growth Potential		Support Requirements
		Business as Usual (BAU)	Aggressive Growth	
Biopower	• Biomass co-firing with coal • Biogas based power generation (particularly landfill gas)	40% increase in capacity from baseline of 10,000 MW to 14,000 MW in 2010 Baseline does not grow and stays at 10000 MW in 2010	• Capacity increases by 100% in 2010 (additional 13,000 MW from baseline of 10,000 MW) • Biopower plants based on advanced BIGCC important in post 2010 timeframe	Modest support, expected to produce power at competitive cost[(a)]
Biofuels	• Starch and/or cellulosic based fermentation technologies for ethanol • Advanced gasification for fuels production for Fischer-Tropsch (FT) diesel	Gasoline additives (e.g. as oxygenates for MTBE replacement) – 50% increase by 2010, 800 MM additional gallons of ethanol over baseline of 1500 MM gallons ethanol in 2010 – Baseline growth results in 200 MM gal. ethanol	• Gasoline additives –100% increase by 2010, additional 2300 MM gallons over baseline of 1600 MM gallons ethanol in 2010 • FT-diesel from gasification in post 2010 period (leverage biopower development) • Baseline grows 300 MM gal ethanol	• Continuation of oxygenates requirement in reformulated gasoline • Continuation of current bio-ethanol fuel tax credit • Extension of tax credit to all bio-derived fuels • Renewable fuel content requirement • Advanced ethanol technology may eventually reduce need for tax credit
Bioproducts	• Fermentation based monomers • Pyrolysis derived phenolics • Specialty lipid-derived products via low temperature processing	• Additional 600 million pounds product in 2010 over baseline of 21 billion pounds products (3% increase) • Baseline grows 3400 MM lbs bioproducts	• 7.5 billion pounds product additional in 2010 over 21 billion pound baseline (35% increase) • Broad implementation of fermentation-based processes, primarily for polymers • Baseline grows 3400 MM lbs bioproducts	• Aggressive government support in technology development and demonstration • In long-term, expect cost competitiveness with petroleum analogs

Source: Arthur D. Little analysis.

(a) Energy prices were based on USDOE EIA's 2001 Annual Energy Outlook, 2010 reference case of $21.4/barrel oil in 1999 dollars. The cost of energy sources was taken from the industrial sector, transportation sector, and electricity generators for 2010, reference case. In each sector scenario, the impacts did not include the baseline activity.

Biopower Options

In the short term, several modest-risk options exist for biopower applications: biogas-based power generation (primarily landfill gas), and the co-firing of biomass in coal-fired power stations. Both options require only limited additional technology demonstration, and have economics that require no or very limited additional support to compete with conventional technologies.

In the post 2010 time frame some biopower options will be broadly cost[5] competitive. Gasification based power generation could further increase the potential for biopower in the post-2010 timeframe. Significant technology improvements in gasification could also benefit other biomass utilization technologies, such as Fischer-Tropsch diesel or other synthesis gas (syngas) based products (e.g. methanol, dimethyl ether).

Biofuels Options

Ethanol used as a gasoline additive or blending agent, supported by the existing tax credit, will provide an attractive option for further expanding the use of bioethanol as a fuel. This represents both an attractive market, and would require no additional government support.

Advances in lower-cost cellulosic biomass ethanol technology may eventually reduce or even obviate the need for this credit or enable further growth of bioethanol fuel use (post 2010). Neat biofuels, in which the ethanol is valued solely on energy content, are expected to continue to require significant additional incentives in order to compete with petroleum fuels under most oil price scenarios. Renewable fuel content standards now under consideration in the U.S. and abroad could provide another means of government support for bioethanol and other renewable fuels.

Bioproducts Options

In the short term, bioproducts based on low temperature processing (such as "engineered" lipids for surfactant and lubricant applications such as hydraulic fluids and cutting oils) are expected to become competitive in certain new markets. Additional bioproducts are expected to attain cost competitiveness with petroleum-derived analogs in the mid too long-term. Bio-monomers for polymer applications have already seen new growth by the evidence of the activities of Cargill-Dow LLC and E.I. DuPont de Nemours. New products are expected to grow by leveraging the tools of biotechnology. Major platforms are expected to use fermentation technology and the processing of lipids to develop a wide range of new products for existing and new applications. Aggressive government support will be required for technology development and demonstration to rapidly commercialize these technologies.

Projected Benefits

This set of options could provide several significant environmental benefits:

- **Considerable reductions in greenhouse gas emissions through a reduction of CO_2 emissions.** Together, all options contribute an overall reduction potential of over 95 million metric tons of CO_2 per year in 2010 in our aggressive growth

[5] Cost comparisons with conventional fuel, power, and product prices are made based on USEIA 's 2001 Annual Energy Outlook for 2010 using the reference case with an oil price of $21.4 per barrel in 2010 (1999 dollars). Clearly, fluctuations in crude oil prices and utility rates could significantly change the competitive position of biomass-derived energy and products. For grid power applications, new electricity capacity was compared to the levelized (all-in) cost of natural gas combined cycle new capacity. New capacity for onsite industrial generation was compared against the projected industrial sector price for electricity from the EIA 2010 projections (from the 2001 Outlook). The incremental cost of co-firing biomass with coal was compared against an average wholesale cost of power.

scenario. Figure 2 below summarizes the air emissions' benefits for biopower, biofuels and bioproducts deployment using a business as usual and aggressive scenario, respectively.

- **Improvements in criteria air pollutant emissions.** Some of the options can lead to significant reductions in criteria pollutant emissions (e.g. co-firing of biomass with coal could lead to significant reductions in nitrogen oxide and sulfur oxide emissions). Aggressive implementation of co-firing biomass with coal can result in 390 thousand metric tons SOx avoided and 440 thousand metric tons NOx avoided, making criteria pollutant reduction a key driver behind the implementation of biomass co-firing. Similarly, application of bioethanol as a transportation fuel will drastically reduce emissions of SOx. Some of the other options would not lead to such clear criteria air pollutant benefits.
- **Biomass production could have some positive impacts on the water and soil quality in the United States**, although very careful management and attention will be necessary to prevent degradation.

Figure 2: Summary of 2010 Environmental Benefits of Implementing Biopower, Biofuel, and Bioproduct Technologies for Two Scenarios

Category	Environmental Benefits in 2010	
	Business as Usual (BAU)	Aggressive Growth
Greenhouse Gas Emissions	• 26 million metric tons per year CO_2 avoided and 24 thousand metric tons per year CH_4 avoided in 2010 for biopower • 5 million metric tons per year CO_2 avoided in 2010 from biofuels • 0.1 million metric tons per year CO_2 avoided in 2010 from bioproducts	• 80 million metric tons per year CO_2 avoided and 87 thousand metric tons per year CH_4 avoided in 2010 from biopower • 14 million metric tons per year CO_2 avoided in 2010 from biofuels • 1.3 million metric tons per year CO_2 avoided in 2010 from bioproducts
Criteria Air Pollutant Emissions	• 130 thousand metric tons per year NO_x and 130 thousand metric tons per year SO_x avoided in 2010 from biopower	• 440 thousand metric tons per year NO_x and 390 thousand metric tons per year SO_x avoided in 2010 from biopower
	• Improvements in criteria pollutant emissions are not a driving factor in biofuel and bioproduct options	
Water and Soil Quality	Biomass production could have some positive impacts on the water and soil quality in the US, although very careful management and attention will be necessary to prevent degradation.	

Source: Arthur D. Little analysis. The estimates in emissions are calculated using a fuel chain analysis. The emission benefits do not include the growth in the respective baselines

The scenarios are defined in later sections of this report. The emissions avoided are estimated as those resulting from activity above the respective baselines (i.e. baseline associated emissions are not included). The estimates in emission reduction are calculated using a fuel chain analysis. For all chains the emissions associated with growing and harvesting the biomass, transporting the biomass and processing the biomass are included. For fuels production, emissions associated with fuel distribution, marketing, and end-use are included. For a full discussion of the assumptions used to estimate the emissions avoided, we refer the reader to the full report and accompanying data volume. A life cycle analysis of the environmental benefits was not part of the scope of this study.

Further, a significant increase in the use of biomass-derived energy and products could add over three billion dollars per year in direct economic activity for rural areas in 2010 from biomass feedstock production alone (primary impact[6], for aggressive implementation). To the extent that this activity offsets overseas gas or petroleum production, it will result in net growth, rather than shifting activity from urban or semi-urban to rural areas. In cases where it offsets domestic resource production (e.g. coal) the impact is a shift in activity, rather than net growth. Additional rural economic activity could also be associated with (pre)-processing of the biomass for production.

The overall nationwide impact of significant increases in use of biomass-based products and energy would nevertheless carry significant net cost (e.g. around $200 million to $2.2 billion per year for the BAU scenario and aggressive implementation scenarios respectively)[7].

Barriers to Implementation

To implement these options, two key inter-linked hurdles must be overcome: improved technology (both existing and new technology) must become commercially available *and* the cost of production of biomass-derived energy and products must be reduced.

Existing biomass utilization uses mostly mature technology and occurs mostly in mature markets. To access new growth markets for biomass-derived energy and products, new applications and new technology must be developed. Key improvements in both process technology cost competitiveness and in new product applications are required to enable broadening of markets for biomass-derived energy and products and include:

- Development of low-cost, high-volume, biomass feedstocks (e.g. energy crops, "harvesting" of agriculture wastes) and the establishment of a large-scale biomass feedstock distribution infrastructure

[6] Approximately $3.4 billion per year in 2010 is the absolute cost of the biomass feedstock alone using an average farm-gate price of $30 per dry ton for aggressive implementation ($1 billion for business as usual implementation). In all analyses gaseous biomass was assigned a zero cost. In addition, process wastes that were used onsite were assessed a zero cost. In this study, tipping fees or negative cost biomass was not addressed. The $3.4 billion per year is the cost for implementing the aggressive scenarios for biopower, biofuels, and bioproducts combined. Additional absolute economic activity occurs as a result of the biomass transportation infrastructure and biomass processing (e.g. power generation, fuels production, or product manufacture) which results in additional economic activity. The reader is referred to the full final report and accompanying data volume.

[7] The "net costs" quoted include the net cost for implementing the BAU and aggressive scenarios for biopower, biofuels and bioproducts combined. The production cost of each category was compared to a competing petroleum chain. The costs of production included the biomass feedstock, petroleum fuel, non-fuel operating costs and a capital recovery charge. For example, the cost of electricity for biomass-derived electricity was compared against the levelized (all-in) cost of new capacity natural gas combined cycle electricity. This difference is reflected in the absolute costs shown. Fuel costs were compared to the projected prices of gasoline from the 2001 EIA Energy Outlook using 2010 energy prices. Tax credits for ethanol fuel was not included. Products were compared to a commodity chemical cost of $0.60 per pound.

- Development and demonstration of low-cost biomass conversion processes, that could result in broader cost-competitiveness for biomass-derived power, fuels, and products in the long-term (post 2010)
- Demonstration of the viability and reliability of technologies currently under development
- Development of new product applications with enhanced performance characteristics compared to petroleum-derived analogs
- Development of optimal information systems to minimize the impact of industry inertia on the market penetration rates of biomass technologies and their applications

The most critical hurdle for broad biomass technology implementation is the reduction of the production cost of biomass-derived energy and products. Given current projections for crude oil and utility prices,[8] most of the long-term options are expected to require considerable one-time investments and carry higher operational costs. Most current biomass technologies are not cost-competitive with fossil-derived fuels, power, and products in new markets without government support. Considerable research, development and demonstration funding will be required to prepare the improved technologies for commercial application. In addition, significant one-time cumulative investments (tens of billions of dollars[9] for aggressive implementation by 2010) will be required for plant construction and infrastructure development to realize the increased production envisioned. Even then many of the options will carry higher operational costs than conventional alternatives.

Eventually, the newly developed technologies could be used for integrated production of biomass-derived energy and products in so-called “Biorefineries”. (Current examples of biorefineries include corn milling and pulp & paper plants.) Integrated production could further improve the cost competitiveness of biomass options with fossil-based counterparts. This will likely require new inter- and intra industry collaborations.

To overcome these barriers, and achieve the aggressive growth targets; three types of support are critical:

- Sustained support for crop (resource) production, biomass conversion, and product use through tax credits, farm supports, and subsidies will be required if the use of biomass-derived energy and products is to be dramatically increased. In addition support will eventually be needed to ensure that the appropriate land is made available for biomass production.

[8] The USDOE EIA 2001 Annual Energy Outlook reference case has a $21.4/B oil price in 2010 (all in 1999 dollars). The 2010 prices are: Industrial sector: electricity $11.2/million BTU; natural gas $3.3/million BTU; Electric generator sector: natural gas $3.0/million BTU and steam coal $1.0/million BTU; Transportation sector: motor gasoline $10.9/million BTU and distillate fuel $8.9/million BTU (excluding taxes).

[9] The investments are absolute, cumulative one-time investments for infrastructure and plant constructions by 2010. For the BAU cases, the estimated one-time investment for biopower, biofuels, and bioproducts combined was 6 billion dollars not taking into account investments that would otherwise be made for similar capacity additions. The absolute cumulative 2010 investment increases to 37 billion dollars (total for implementation for biopower, biofuels, and bioproducts) if the aggressive scenario is implemented in its entirety.

- Strong fiscal and regulatory support for near-term biomass opportunities. This could include continuation of existing tax credits, implementation of investment incentives, renewable content standards, and streamlining of the regulatory and permitting process for biomass-based facilities.
- Strong support for research & development and demonstration (R&D/D) focused on long-term improvements in technology that will eventually make the technology cost-competitive with conventional (e.g. fossil-derived) products, fuel and power sources.

Coordination and careful planning of such support will be critical to its success; a role that could be played by organizations such as the USDOE, USEPA and USDA.

Our full report and its accompanying data volume provide more in-depth perspective on the rationale behind these findings. Thus, for even more detail, we refer to the complete presentation-style report, “Aggressive Growth in the Use of Bio-derived Energy and Products in the United States by 2010, Final Report” and its accompanying Data Volume.

Background and Objectives

In the Spring of 2000, the United States Department of Energy (USDOE) selected Arthur D. Little to identify strategies to increase significantly the consumption of bio-derived energy, fuels and products by 2010; the results of which are summarized in this report. The underlying objectives for the study were based in part on the Biomass Research and Development Act of 2000 (Public Law 106-224), the National Sustainable Fuels and Chemicals Act of 1999 and Former President Clinton's Executive Order 13134 "Developing and Promoting Biobased Products and Bioenergy." These documents identify that increased biomass use for energy and product applications may help to:

- Reduce the environmental burden of producing energy and materials
- Stimulate rural economic development
- Improve U.S. balance of payments position
- Improve U.S. energy security
- Accelerate the development of competitive U.S. technology

The objectives are also supported by the George W. Bush Administration's National Energy Policy[10]:

- Biomass provides a domestic source for energy and fuels for the future
- Increased production and utilization of biomass will utilize environmentally friendly technology that will increase energy supplies and help raise the living standards of the American people, particularly in rural and semi-rural areas

It was recognized from the start that opportunities could be categorized into three key sectors, based on the end products:

- *Biopower* and bio-heat (e.g. woody biomass-fired power plants, co-firing of biomass with coal or with natural gas, utilization of landfill gas)
- *Biofuels* (onroad transportation fuels such as bioethanol, biodiesel, bio-Fischer-Tropsch[11] diesel both as neat fuels and as fuel additives)
- *Bioproducts* (primarily carbohydrate and lipid based chemicals) both for new and existing products and applications

[10] "National Energy Policy: Reliable, Affordable, and Environmentally Sound Energy for America's Future", Report of the National Energy Policy Development Group, May 2001

[11] Fischer-Tropsch (FT) synthesis chemistry can be used to produce a range of chemicals and fuels from synthesis gas, including diesel, naphtha, and waxes.

The objective of this report is to identify options in each of the sectors mentioned above that could contribute substantially to the goal of significantly increasing biomass use, and to evaluate to what extent they achieve each of the five beneficial effects mentioned above.

Scope, Approach, and Study Limitations

Scope & Approach

The scope for this report was defined initially in the request for proposals that precipitated this project. Subsequently, USDOE and Arthur D. Little jointly interpreted the defined scope of the study. First, the report is focused on opportunities for biomass that could have a significant impact (in terms of energy use, environmental performance, or effects on rural economic activity) by 2010, in keeping with the aggressive growth goals of the study.

The study that formed the foundation for this report followed a four-task approach:

Task 1	A biomass resource assessment (reviewing existing data and identifying critical gaps)
Task 2	Identification and analysis of options (evaluating and screening for the most attractive options based on market potential, technology status, infrastructure requirements, and cost competitiveness)
Task 3	Analysis of benefits and impacts (assessing the environmental benefits and the impact on the national and rural economies of each of the selected options); Note: a full life cycle analysis was not part of the scope of this study
Task 4	A scenario analysis (forecasting the use of biomass-based energy and products under a business as usual and an aggressive growth scenario, and then evaluating the policy options that may be available and/or necessary to achieve the desired goals)

The study excluded several conventional products currently made using biomass resources. The categories that were excluded from the scope are summarized in Figure 3 below. USDOE and USDA made the selection of included categories of products.

Figure 3: Summary of Categories That Were Excluded From Scope of Analysis

	Excluded from Analysis	Comments
Fuels	• None were excluded • Fuels for transportation applications were emphasized	• All fuels derived from biomass for on-road transportation applications were considered • Both pure fuels and fuel blending agents or additives were considered
Electricity and heat	None were excluded	• The steam (heat) and power generated by traditional biomass based industries such as the pulp&paper industry was included to take into account industry efficiency improvements • Included both grid and onsite power applications
Bioproducts	• Paper, lumber and other conventional wood products • Food, food ingredients and food by-products • Pharmaceutical and "nutraceuticals" • Textiles	• The actual product of the pulp&paper was excluded but the heat and electricity generated were included • Food and food by-products were excluded both for human and animal consumption (including animal bedding) • The scope was on large volume (by mass) markets so that pharmaceuticals were excluded; high-value products such as pharmaceuticals may be part of a biorefinery concept • Textiles involving natural fibers were excluded; also composites for wood and lumber applications using crop residues were also excluded

Source: USDOE and Arthur D. Little jointly defined the scope of work

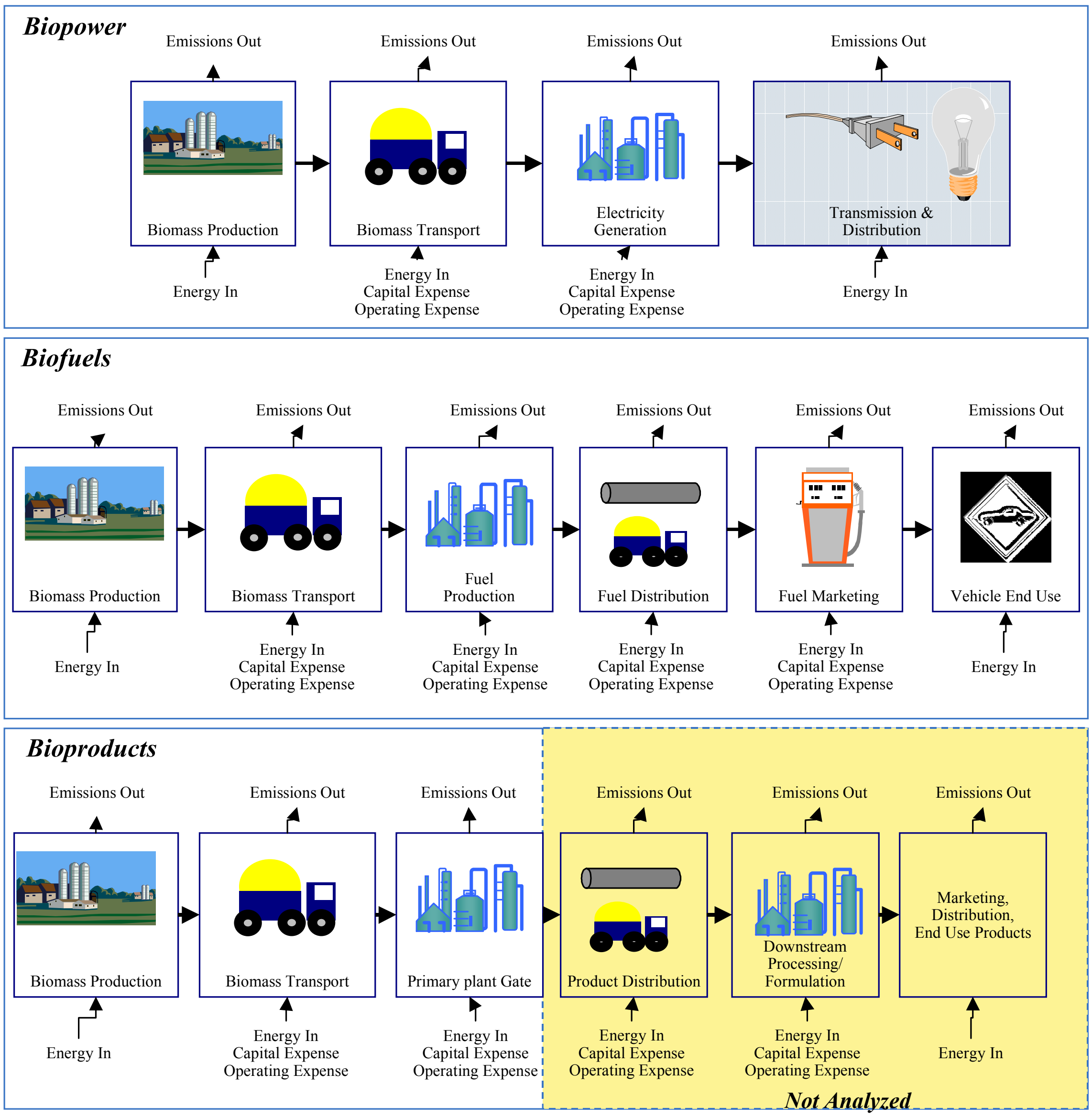
The analysis was based on available information and data, for the biomass production, conversion, and for the performance and cost parameters of the technologies under consideration. However, for those bioproduct technologies where no suitable information was publicly available, original estimates were made by analogy with other processes. Pointers to references can be found throughout the report, while a complete list of the references is found in the Appendix. The overall assumptions for each technology module are also included in the Data Volume of the full report.

Throughout the study, each potential fuel/power/product was analyzed on a "value chain" basis, including impacts from plantation/collection site to the market of use. This allows a capture of the relevant direct energy and feedstock inputs into each of the steps in the value chain, but not the indirect inputs. The methodology considered energy inputs into the value chain up to so-called second order effects (e.g. energy consumed to produce diesel fuel for a tanker truck was included, but not the energy used to produce the tanker truck, similarly, methane emissions from coal mines are included, but not the energy consumed in producing the mining equipment.

For all bioenergy chains an assumption was made that there would be no net emissions associated with the short-cycle carbon (i.e. the carbon contained in the biomass itself). The underlying thought being that the emissions from the oxidation of this carbon would be offset simultaneously by the biomass growing at that time. Similarly, methane or other emissions that are either avoided by or caused by the production and handling of biomass that are not caused by the use of fossil fuels were assumed to be net zero.

While some consider that this underestimates the benefits of biomass use (e.g. by collecting forest residues natural rot would be reduced and hence methane emissions) others argue that those emissions are associated with natural (i.e. non-anthropogenic) sources and should therefore not be counted. CO_2 emissions from the combustion of fossil fuels associated with biomass production (such as those from logging equipment using fossil fuels or "harvesting" agricultural residues) are included in our analysis. Figure 4 illustrates the basic chain elements in the value chain analyzed for all three sectors of the study. A summary of the key assumptions for each sector of analysis is shown in Figure 5; complete assumptions of the analysis can be found in the full report and accompanying data volume.

Figure 4: Illustration of Value Chain Analysis for Evaluation of Economics and Environmental Benefits



Source: Arthur D. Little analysis.

- The value chain analysis is not a life cycle analysis. The value chain analysis considers most steps involved in production and use of biomass energy, fuels and products. It incorporates multiplicative effects in the value chain and allows for detailed analysis of each module and consideration of a range of combinations. The methodology considers all energy inputs into the value chain, including secondary not tertiary inputs; i.e. energy used to produce diesel for trucks is included but energy use to make the trucks or the refinery is not included
- The costs associated with biomass production (e.g. land, labor, seed, fuel, capital recovery) are assumed to be reflected by the price ($ per dry ton farm-gate) of the biomass. Emissions associated with biomass production are included (e.g. from fertilizer and petroleum fuel use) in the benefits and impact analysis. For biopower and biofuels applications the carbon in the biomass is assumed to be net zero closed loop biomass.
- Biomass transport costs and emissions are associated with a 50-mile one way trip by a diesel fueled truck
- For biopower, cases using biomass co-firing include only the costs and emissions associated with implementing the biomass portion. Energy losses are included for transmission and distribution but not the associated investment costs for grid power applications.

- For biofuels, the costs associated with distribution to a fuel depot and transportation to fueling stations are included if the existing petroleum infrastructure is not sufficient. Vehicle end use includes the efficiency of the vehicle with the fuel. Costs associated with vehicle modifications are not included
- For bioproducts, The cost and associated emissions of products was estimated from biomass production to primary product manufacture and ended at the primary plant gate. All downstream costs and associated emissions involved in primary product transportation, marketing & distribution, and further downstream processing, distribution and end-use are not included.

Figure 5: Summary of Assumptions Made for Biomass Value Chains for Each Sector

<table>
<tr><th></th><th colspan="2">Environmental Benefit Analysis</th></tr>
<tr><th></th><th>Options</th><th>What was addressed</th></tr>
<tr><td rowspan="2">Biomass Production and Harvesting</td><td>• Agricultural residues (e.g. corn stover, wheat straw)
• Cellulosic energy crops (e.g. hybrid poplar, switchgrass)</td><td>• Emissions for agricultural residues and the main crop (e.g. corn or wheat) were assigned equal emissions on an energy basis
• Estimates for agricultural residues and energy crops includes energy required for fertilizer production in addition to fuels used for farm equipment
• For fertilizer use (both for agricultural residues and energy crops) the emissions are based on the energy embodied in the fertilizers (gas & electricity), neglecting energy for transportation of the fertilizer
• A multiplier was used for seeds, herbicides, pesticides and assumed to be 10% of the energy embodied in fertilizer for agricultural residues and energy crops
• A 50/50 mix of best available control and uncontrolled technology were used for the emission factors emissions associated with fertilizer and planting & harvesting of agricultural residues and energy crops
• For energy crops we assumed that the same fuel distribution as used for corn farming; also that 1/2 of the land is not fertilized</td></tr>
<tr><td>• Gaseous biomass
• RDF
• Process wastes (e.g. black liquor, hogged fuel, other solid residues)</td><td>• Biogas (including landfill, sewage, and digester gas) is generated and used where it is produced so there is no energy use (and therefore no emissions) associated with biomass “harvesting” or gathering and subsequent transport of the resource
• For biogases, fugitive CH_4 , nonmethane hydrocarbon (NMHC), and particulate matter (PM) emissions that would have occurred regardless of the end use for the biogas were also excluded
• For RDF, the emissions associated with collection and processing are not included as these would need to be done regardless of the use of RDF for fuel (The non-biomass portion of RDF is also excluded). The RDF is used at the collection site so that transportation emissions are not included
• Process wastes (including black liquor, hogged fuel, and other solid residues) are generated and used where produced so there is no energy use (and therefore no emissions) associated with biomass gathering and transport of the resource</td></tr>
<tr><td>Biomass Transport</td><td>• Agricultural residues
• Cellulosic energy crops</td><td>• Transportation emissions are associated with a 50-mile one-way trips using a diesel fueled truck. A 50/50 mix of best available control technology and uncontrolled was used for the emission factors</td></tr>
</table>

	Environmental Benefit Analysis	
	Options	**What was addressed**
Biopower	• Resources – Biogases (e.g. landfill, sewage, & digester gases) – Agricultural residues – Energy Crops – RDF – Black liquor – Hogged fuel – Other solid residues • Technologies included: – Rankine cycle – Gas turbine – Gas turbine combined cycle – Integrated gasification combined cycle – Internal combustion engine – Fuel cell	• CO_2 emissions from the utilization of the biomass itself are assumed to be zero (closed-loop carbon cycle) • Biogas (including landfill, sewage, & digester gas), RDF, black liquor, hogged fuel, and other solid residues are generated and used where it is produced so there is no energy use (and therefore no emissions) associated with transport. Fugitive CH_4, NMHC, & PM emissions that would have occurred regardless of the end use were also excluded • Grid-sited options (e.g. utilization of landfill gas, co-firing with coal) include the effects of transmission & distribution energy losses • Most biomass is relatively low in sulfur and therefore no controls are used. For selected feedstocks that are higher in sulfur, such as black liquor, sulfur control technology was used • Fuel cell emissions of SO_2 are effectively zero, as the fuel must be scrubbed free of sulfur to avoid poisoning of the fuel cell stack • NOx emissions estimates are consistent with typical controls (e.g., dry low NOx combustion for gas turbines, lean burn technology for IC engines) • For co-firing with coal it is assumed that each percentage point of biomass co-firing results in a 2 percentage point decrease in overall NOx for direct firing and a 4 percentage point decrease for gasification co-firing (the latter is consistent with the use of the biomass as a reburn technology) • For co-firing with coal it is assumed that methane, NMHC and CO emissions are the same per BTU of fuel consumed as for the baseline coal plant, so that differences in emissions per kWh are related to differences in efficiency • For biomass co-firing with coal, the co-firing is assumed to reduce PM emissions based on the relative ash content of biomass and coal • Methane, NMHC emissions are generally uncontrolled emissions consistent with current good practices for combustion (e.g., dry low NOx combustion for gas turbines, lean burn technology for IC engines) • PM emissions are generally controlled emissions consistent with current good practices (e.g., electrostatic precipitators) • CO emissions are generally uncontrolled emissions consistent with current good practices for combustion (e.g., dry low NOx combustion for gas turbines, lean burn technology for IC engines)

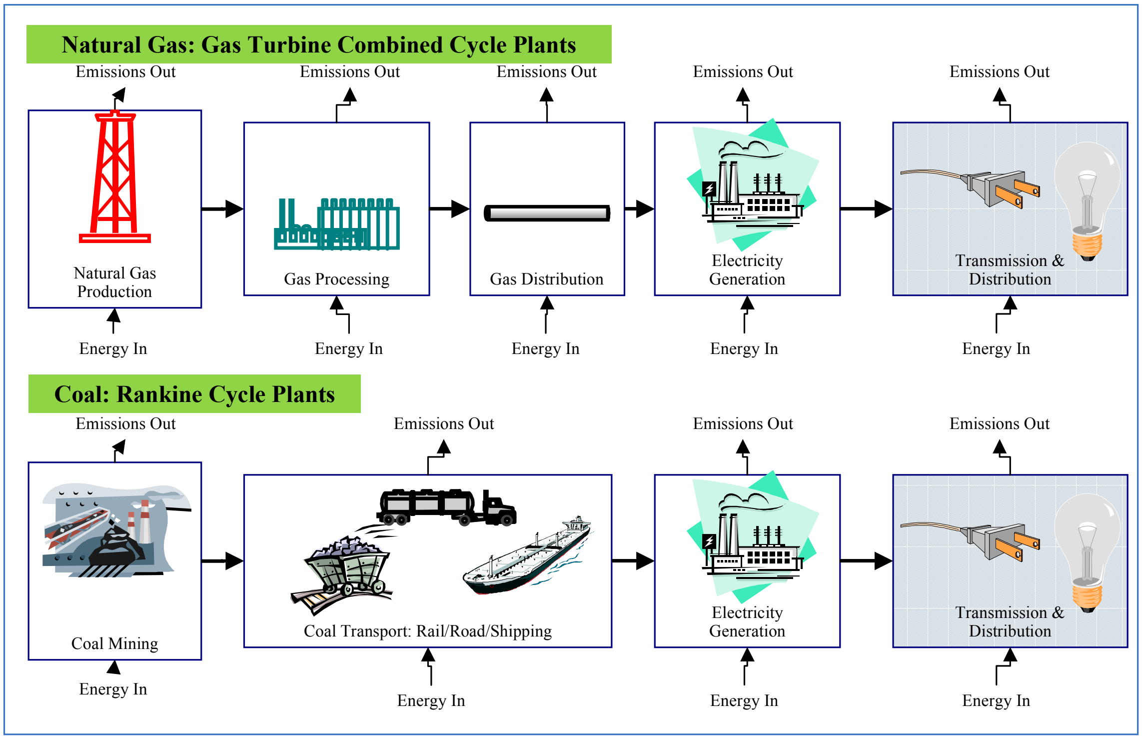
	Environmental Benefit Analysis	
	Options	**What was addressed**
Biofuels	• Agricultural residues • Energy Crops • Corn • Technologies included: – Ethanol production from corn – Ethanol production from cellulosics – Fischer-Tropsch diesel production from agricultural residues or energy crops	• CO_2 emissions from the utilization of the biomass itself or its end product (i.e. the produced fuel) are assumed to be zero (closed-loop carbon cycle) • Carbon dioxide and sulfur dioxide are based upon the elemental composition of the fuel and the chain efficiency • For fuel manufacture emissions within the plant gate are assumed to be from best available control technology. The exception is any vehicles used to move the biomass within the plant gate. These vehicles are assumed to be fueled with petroleum-diesel and have 50/50 emissions associated with a mix of uncontrolled and best available control technology • All electricity used for manufacture of the fuel used a grid average mix for emissions estimation • Emissions are included for distribution of the fuel to depot stations and transport to retail stations. Evaporative losses are included for retail marketing of the fuel • Emissions are associated with the biomass portion of the fuel only • The vehicle emissions are based on that the vehicle is designed to meet the emission standard (ULEV), regardless of the fuel used. Regulated emissions for each fuel are set by the relevant emission standards – NOx, CO, and nonmethane hydrocarbon standards are set by the 50,000 mile durability ULEV standards for 2001-2006 Model Year for All passenger car's and light-duty trucks (0-3750 lbs LVW) – Particulate matter for compression ignition engines are the 100,000 mile durability standards for new 2001-2003 Model Year TLEV passenger cars and light duty trucks – Methane emissions are calculated from correlations based on the amount on nonmethane hydrocarbon emissions – The effect of ethanol as an oxygenate on emissions in the vehicle was not taken into account

	Options	What was addressed
Bioproducts	• Agricultural residues • Energy Crops • Seed oils • Corn • Technologies included: –Fermentation –Oil Splitting of lipids –High temperature pyrolysis –Syngas based processes	• The biobased chemicals value chains were analyzed up to the wholesale level. Thus we did not analyze the potential impacts of changes in product design and usage. The implicit assumption was that the biobased chemicals would have comparable performance. For example, any increases or decreases in the weight of the final products could impact transportation costs of the products, or change energy use in the use of the product. • Also, energy use and emissions impacts associated with the end of the life of the chemical is not considered. We expect that on balance, the impact of this limitation will be neutral, since some bio-based chemicals will perform better, while others will perform less well. • For primary product manufacture, emissions within the plant gate are assumed to be from best available control technology. The exception is any vehicles used to move the biomass within the plant gate. These vehicles are assumed to be fueled with petroleum-diesel and have 50/50 emissions associated with a mix of uncontrolled and best available control technology • All grid electricity used for manufacture of the primary product used a grid average mix for emissions estimation • For fermentation based processes utilizing glucose; we included the comparable emissions to grow and transport the raw corn but did not include the emissions associated with making the glucose from starch in a wet or dry corn mill • Similarly for oil seed based materials; the emissions were assessed for the processing of the seed oil to make the product but did not include the upstream emissions associated with growing the plant, harvesting the seed, transporting the seed, and recovering the raw oil from the seed • Fugitive emissions from biomass stockpiles on the plant site or fugitive emissions associated with unused crop or resource materials were excluded

Source: Arthur D. Little analysis

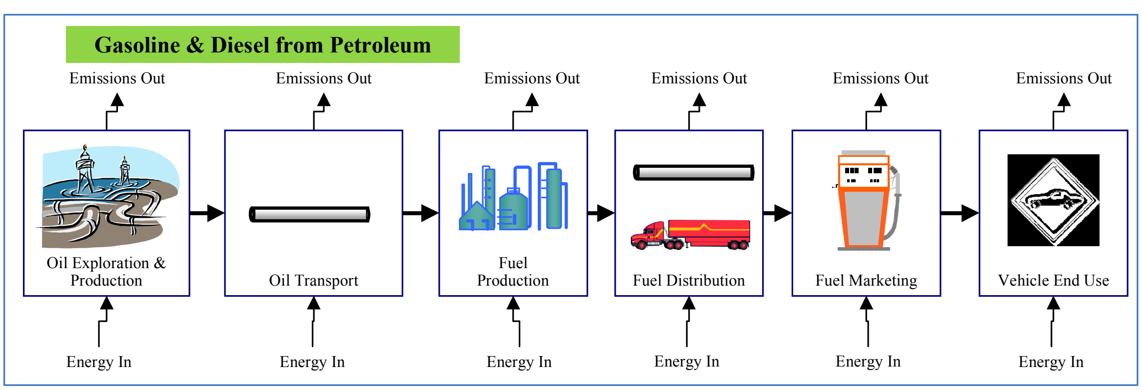
For the fossil alternatives, similar value chains were constructed for coal-based electricity; natural gas-fired gas turbine combined cycle, and gasoline and diesel fuels from petroleum. For the bioproducts analysis, because of the diverse slate of options, two proxies were made for a high level comparison for a primary industrial product: methanol from natural gas and liquefied petroleum gas (LPG) from petroleum. Figures 6, 7, and 8 show the basic elements in the fossil fuel analogs for each sector. Figure 6 shows the fuel chain elements of natural gas fired combined cycle power generation and coal-fired Rankine power generation. Figure 7 illustrates the fuel chain elements of motor gasoline and diesel from petroleum. Figure 8 is an example of an industrial intermediate, methanol from natural gas. The assumptions included in the fossil chains are summarized in Figure 9. The analysis of the environmental impacts and costs reflect the difference between the proposed new value chains and the current situation (e.g. conventional technology, using feedstocks derived from fossil fuels). For example, in the implementation of bioethanol as a neat fuel, the costs and emissions are compared with a conventional gasoline from petroleum value chain including use in the vehicle.

Figure 6: Illustration of Value Chain Analysis for Evaluation of Economics and Environmental Benefits of Power Generation from Fossil Fuel Resources



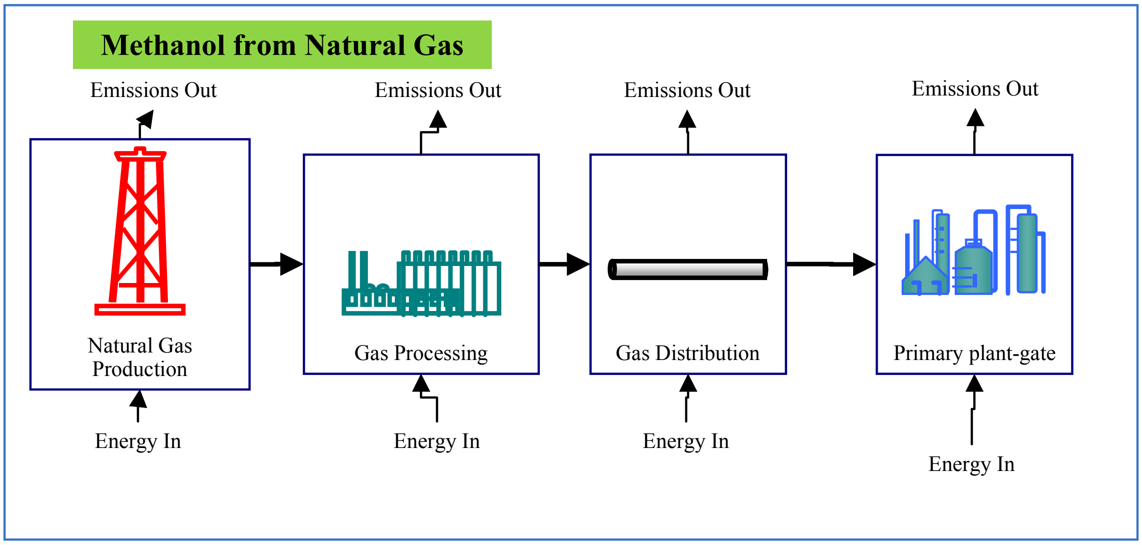
Source: Arthur D. Little analysis

Figure 7: Illustration of Value Chain Analysis for Evaluation of Economics and Environmental Benefits of Gasoline and Diesel Transportation Fuels Derived From Petroleum



Source: Arthur D. Little analysis

Figure 8: Illustration of Value Chain Analysis for Evaluation Environmental Benefits of Methanol Derived from Natural Gas (An Example Industrial Intermediate)



Source: Arthur D. Little analysis.

Figure 9: Summary of Assumptions Made for Fossil Alternative Value Chains

	Coal Rankine Electricity	Natural gas GTCC Electricity
Exploration & Production	• Emissions are associated with coal mining based on 1987 U.S. Coal Industry Statistics and DeLuchi, November 1993, based on DoC Census • Coal bed methane production and its end disposition is included (90% vented; 10% used for fuel)	• Emissions are associated with extracting the natural gas from the well head and associated emissions from processing of the gas (e.g. removal of inerts, recoverable products (NGLs, LPG), and removal of impurities) • Vented and flared gas is assumed to be associated with petroleum oil production and is included in the petroleum value chain; the natural gas is flared or used as fuel onsite
Fuel Transport	• Emissions are associated with a transportation mix of ship (18%), rail (65%), and truck (15%); transportation mix based on DeLuchi; total transport amount from 2000 data	• Emissions associated with national average pipeline for natural gas. Based on total Natural gas supply since this is the amount shipped through U.S. pipelines annually.
Electricity Generation	• Coal Rankine power production with a HHV efficiency of 32.9% • Did not include steam (heat) production credit • Transmission & distribution energy losses of 7.2%	• Natural gas-fired GTCC power production with a HHV efficiency of 54.0% • Transmission & distribution energy losses of 7.2%

	Gasoline From Petroleum	Petroleum Diesel
Exploration & Production	• Petroleum extraction from Petroleum Extraction - 1987 DoC Census Data adjusted by DeLuchi (1993) including Alaska and Lower 48 Production • Includes natural gas flared during production. The natural gas is flared or used as fuel onsite • Segment efficiency 95.8%	
Raw Oil Transport	• Emissions are associated with shipping crude oil within Lower 48 and from Alaska to Lower 48 and shipping of oil imported into United States. • Modes of transport included pipeline, barge, tanker, train, and truck • Includes evaporative losses; segment efficiency of 99.1%	
Fuel Production	• Includes refining from petroleum for gasoline production with a segment efficiency of 87.8%	• Includes refining from petroleum for gasoline production with a segment efficiency of 94.8%
Fuel Distribution	• Includes emissions associated with transport of the gasoline to the bulk terminal by a combination of pipeline; tanker and barge; truck transport to the bulk plant and truck transport to the fueling stations	• Includes emissions associated with transport of the diesel to the bulk terminal by a combination of pipeline; tanker and barge; truck transport to the bulk plant and truck transport to the fueling stations
Fuel Marketing	• Includes energy usage at fueling stations and evaporative losses	• Includes energy usage at fueling stations and evaporative losses
Vehicle Use	• Use in spark ignition vehicle with 15.7% efficiency • Emissions are set to ULEV standards	• Use in CIE vehicle with 16.9% efficiency • Emissions are set to ULEV standards • Particulate matter set to 100,000 mile durability standards for new 2001-2003 Model Year TLEV vehicles

	Proxy Industrial Primary Products	
	Methanol from Natural Gas	**LPG from Petroleum**
Exploration & Production	• Emissions are associated with extracting the natural gas from the well head and associated emissions from processing of the gas (e.g. removal of inerts, recoverable products (NGLs, LPG), and removal of impurities)	• Petroleum extraction from Petroleum Extraction - 1987 DoC Census Data adjusted by DeLuchi (1993) including Alaska and Lower 48 Production • Includes natural gas flared during production • Segment efficiency 95.8%
Raw Fuel Transport	• Emissions associated with national average pipeline for natural gas. Based on Total Natural Gas Supply since this is the amount shipped through U.S. pipelines annually.	• Emissions are associated with shipping crude oil within Lower 48 and from Alaska to Lower 48 and shipping of oil imported into United States. • Modes of transport included pipeline, barge, tanker, train, and truck • Includes evaporative losses; segment efficiency of 99.1%
Primary Product Manufacture	• Methanol synthesis from synthesis gas made from natural gas with segment efficiency of 66.5%	• Includes refining from petroleum for LPG production with a segment efficiency of 95.3%

Source: Arthur D. Little analysis based on work by DeLuchi, Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, Volumes I and II, Center for Transportation Research, Argonne National Laboratory, November 1993.

Study Limitations

Notwithstanding the size of this report, the definition of the scope described above carries with it a number of significant limitations. It is critical to understand these limitations when reading the report, and even more so when using the information contained within it. To that end, the most important limitations are described below. Of course this does not absolve the reader from the responsibility to read the caveats made throughout the report and to read the footnotes on the pages.

The most important limitation to understand results from the timeframe considered in the scope. The study focused on near-term (up to 2010) *and* high-impact solutions. This is a significant restriction. The 2010 target focuses attention on technologies that are close to commercialization (have at least been proven at pilot scale). At the same time, it focuses on technologies that could have broad impact. This excludes many technologies from consideration. An artifact of the scope of analysis is that some longer-term technologies (post 2010) that could have higher overall impact were excluded (e.g. some of the advanced fermentation-based bioethanol technologies as well as biological production of hydrogen were excluded for this reason). Conversely, other options that may be attractive in the near-term but do not have the potential for broad impact in the long-term were excluded. For example, negative feedstock values are unlikely to be sustainable in a long-term, high-impact scenario, but could provide quite attractive opportunities for early entrants in the near-term (e.g. Masada MSW to ethanol projects). Similarly, the use of idled capacity plants (e.g. paper mills, biopower plants, etc.) could provide significant capital cost advantages for some early applications (especially in California). The entire list of options considered (for biopower, biofuels, and bioproducts) and a summary of the screening results is summarized in the appendix of this report.

A second limitation of the study that must be understood, is the treatment of the economic impact of environmental degradation and of the use of natural non-renewable resources. As do most economic analyses, this study considered such economic impacts of environmental degradation and natural resource use as externalities (i.e., they are not included in the economic evaluation). This is a common approach, as it is difficult to quantify such impacts. Some researchers internalize these factors into the economic evaluation, which negatively affects the economics of less environmentally friendly technologies. The inclusion of externalities can result in bioenergy and bioproducts being more competitive with fossil fuel-based analogs. On the other hand some argue that the use of public lands to produce biomass should then also be internalized. As there is no accepted treatment of these externalities, they are not included in the report. Environmental benefits and impacts are recognized as valuable throughout the report as key policy drivers behind the desire to increase biomass use for energy and products.

In some cases environmental factors are internalized through regulatory instruments. An example is the NO_x and SO_2 emissions trading. For example in the case of biomass co-firing with coal, the sale of NO_x and SO_2 credits provides a means of internalizing some of the cost of NO_x and SO_2 emission avoidance. If similar credit systems were to be implemented for other pollutants (e.g., CO_2) it could well help the competitiveness of other biomass options. The importance of environmental protection is explicitly included in this report as one of the underlying and motivating policy objectives.

A third general limitation of the study lies in what is and what is not included in the analysis. While the analyses cover the entire value chain, and while they cover all direct energy and feedstock inputs, they are not full lifecycle analyses. For example, the environmental impact of the construction of conversion plants is not considered in this analysis. This limitation tends to favor new value chains, as the environmental impact of new equipment is not considered, while conventional value chains typically do not require the same level of new construction.

Similarly, secondary effects of the use and production of biomass are not considered. For example, in our analysis we consider biomass to be simply short-cycle carbon, and that it has no net impact on CO_2 or other greenhouse gas emissions, other than that associated with the fossil fuels and fertilizer used in the production. However, some would argue that the use of biomass for energy or chemicals production would reduce the amount of rot that occurs on fields and amount of materials disposed in landfills and hence the emissions of, for example, methane. Conversely we also did not include any potential increases in emissions due to rot in biomass storage piles. In general though, it is thought this limitation disfavor's biomass-based value chains. The biomass value chains would be more likely to establish incentives and infrastructure to manage the emissions.

Also, as described above, the biobased chemicals value chains were analyzed up to the wholesale level. Thus we did not analyze the potential impacts of changes in product design and usage. The implicit assumption was that the biobased chemicals would have comparable performance. For example, any increases or decreases in the weight of the final products could impact transportation costs of the products, or change energy use in the use or of the product. Also, energy use and emissions impacts associated with the end of the life of the chemical is not considered. We expect that on balance, the impact of this limitation will be neutral, since some bio-based chemicals will perform better, while others will perform less well.

Baseline Biomass Use

Currently, biomass resources constitute a small fraction of the overall primary U.S. energy mix (3 percent of energy use)[12]. Similarly, aside from the production of paper, wood and lumber products, food and feeds, and textiles, biomass accounts for a small portion of U.S. materials production. When looking at total biomass energy use, industry is the largest user, and the largest energy application is for heat (e.g. steam production). Wood is the largest biomass resource currently used. In the United States, 75% of non-hydro renewable power generation is biomass-derived, accounting for 1.5% of total power generation. Biomass fuels (mostly ethanol) represent less than 1% of the total U.S. transportation fuel consumption and represent about 20% of alternative fuel use (other alternative fuels include MTBE and compressed natural gas). Wood and starch applications for non-paper products, applied for selected materials and chemicals, represent a much smaller market.

Because the target set in the objectives for the study was a relative one (significant increases, e.g. more than doubling), establishing a clear baseline was critical. Although biomass contribution is significant for wood and paper products, as well as for foods, food additives, and feeds, these applications were excluded from the scope and thus from the baseline. (See Figure 3 for specific categories that were excluded). Heat and power from the pulp & paper industry were included in the baseline for this study whereas the products from the industry (e.g. paper, pulp, and wood products) were excluded.

Figure 10 summarizes the baseline use on an output basis in terms of biomass mass, energy and monetary value of the products. Current annual use of bioenergy, biofuels and bioproducts on an output basis amounts to 108 million tons, with a product energy value of 1.9 million TJ (~2 Quads), or product monetary value of $14 billion (excluding out of scope categories)[13]. The mass basis is on an output basis; the actual biomass utilized would be greater because of process inefficiencies.

[12] 1998 data except for products data use that is based on 1989 data. References include DOE/EIA *Renewable Energy Annual 1999* (DOE/EIA-0603(99)); DOE/EIA Electric Power Annual 1998; Pulp and Paper 1999-2000 North American Factbook (1997 data); *Transportation Energy Data Book, Edition 19 (ORNL-6958); The Carbohydrate Economy, Institute for Local Self-Reliance, August 1992.*

[13] The mass basis was estimated by the equivalent mass of biomass using an average biomass energy density. The energy basis is the energy content of the actual category. Energy prices from the EIA 2001 Energy Outlook, 2010 reference case, were used to evaluate the value of each category. The exception is for bioproducts that were assigned a nominal value of $0.30 per pound.

Figure 10: Baseline Use of Biomass on an Output Basis (Excluding Out of Scope Categories)[14]

Category	Baseline Annual Production: Output Basis			
	Conventional Units	Output Mass-basis[1] (tons)	Output Energy-basis[1] (TJ, 10^{12} J)	Output Economic-basis[1] ($MM value)
Biopower				
Pulp & paper industry steam production[1,2]	1.4 billion MMBTU	82 million	1,440,000	$6000
Electricity production from wood & wood wastes[1,2]	33 billion kWh	6.8 million	120,000	$1300
Electricity production from MSW[1,2]	19 billion kWh	3.9 million	69,000	$730
Electricity production from other biomass wastes[1,2]	3.4 billion kWh	690,000	12,000	$130
Biofuels				
Ethanol	1.3 billion gallons	6.4 million	113,000	$1,200
Bioproducts				
Industrial products	8.7 million tons	8.7 million	121,000	$5,200
Total		**108 million**	**1.9 million**	**$14,600**

Source: Arthur D. Little analysis based on EIA data.

1. Output mass basis is the mass equivalent of the category based on a biomass energy density of 17.5 GJ/ton; the actual amount of biomass used to make the product is higher due to process inefficiency (mass shown is on an output basis). Industrial products have been estimated to have an energy density of 80% of raw biomass (0.8 X 17.5 GJ/ton = 14 GJ/ton). The energy basis is on an outlet basis. The economic value is based on steam valued at $4.4/millionBTU; motor gasoline $10.9/millionBTU (also ethanol); industrial electricity $11.2/millionBTU (EIA 2001 Energy Outlook 2010 reference case); industrial products $0.30/lb).

2. Pulp & paper steam production was estimated from 100% of wood & wood wastes is in the pulp & paper industry that is converted into electric power at 20% efficiency with 80% of waste heat recovered

[14] Biopower: Pulp & Paper Industry Steam Production: Estimated that 100% of electricity production from wood & wood wastes is in the pulp & paper industry and is converted into electric power at 20% efficiency with 80% of the waste heat recovered. Difference between actual use of hog, bark and spent liquor solids as internal fuels and implied need at 20% generation efficiency is assumed to be converted directly into heat and used onsite. (Data from Manufacturing Consumption of Energy Survey, EIA). Electricity Production from Wood & Wood Wastes; Electricity Production from MSW; Electricity Production from Other Biomass Wastes from the EIA Renewable Energy Annual 1999. Biofuels: For ethanol: Energy Information Administration (EIA) website: http://www.eia.doe.gov/cneaf/solar.renewables/alt_trans_fuel98/table10.html, 1999 data. Bioproducts: Ahmed & Morris, The Carbohydrate Economy, 1992

Biomass Feedstock Availability and Environmental Impacts

Sufficient biomass resources could be made available to more than double the use of biomass for power, fuel, and product applications. Even if the appropriate regulations and policies were in place to achieve this, prices are expected to exceed $20/dry ton at the farm-gate as demand for biomass feedstocks grows to the levels associated with doubling of biomass use (as defined for this study). Available literature data indicates that:

- A total of over 600 million dry tons of biomass are available within the United States at farm-gate prices between $0 and $40 per dry ton (equivalent energy value of 0 to $2.3/GJ or $2.4/millionBTU using a heating value of 17.5GJ/dry ton)[15].
- High-quality biomass is not available in large quantities below $20/dry ton farm-gate (e.g. agricultural residues and energy crops, see Figure 6). With biomass costing less than $20/ton, it would not be possible to achieve the significant increases targeted in this study.
- Those biomass resources that are available in significant quantities below $20/dry ton farm-gate are mostly wastes, many of which are relatively heterogeneous (e.g. organic municipal solid waste and urban tree residues).
- Ultimately, at very high levels of biomass use, according to predictions made with USDOE's agricultural sector model, energy crops would likely be the largest source of biomass at farm-gate prices greater than $40/dry ton[16]. However, energy crops such as hybrid poplar, switchgrass, and willow are currently not produced in high volume.

For perspective, a farm-gate price of $40/ton amounts to a little over $12.00/barrel of oil equivalent, which would be problematic for many processes given the typical efficiencies and capital costs of biomass conversion processes (at EIA's projected oil prices of $21/barrel for 2010). Alternatively, $40/ton amounts to about $2.40/millionBTU, compared with projected coal prices of between $1.00 and $2.00 / million BTU. Thus, biomass feedstock cost is expected to remain a very significant portion of overall cost when high-volume use of biomass is the objective. Of course the importance of cost in general will not be as serious if fossil energy prices were to be substantially higher, such as in the Spring of 2001 (around $30/ barrel oil and over $4.00/ million BTU for gas).

Figure 11 consists of supply curves for available biomass resources developed in this study based on literature data. Supply curves were not developed for traditional crops such as corn, soybean or rapeseed. Rather, average market prices and volumes are

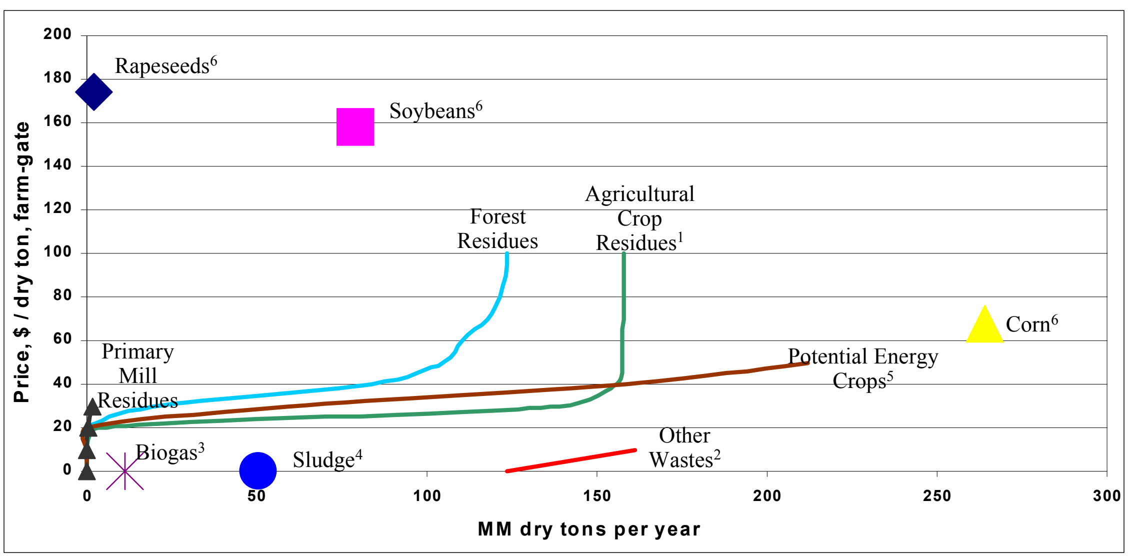
[15]An independent assessment of the available resource data was not part of the scope of this study. Literature sources are listed in the reference section under the resource subsection.

[16]Model results were obtained from Ugarte, D., M. Walsh, H. Shapouri, and S. Slinsky (July 2000), "The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture". Additional resource references are in the appendix to this report.

shown. Biogases and sludge were assumed to be zero cost resources. Figure 11 does not include raw biomass transportation costs or further costs of processing the biomass (e.g. fuel or power production). These costs are incorporated into the estimates for the cost of the applications (e.g. ethanol production full fuel chain cost, fuel chain cost of electricity, etc.). The following categories were addressed in the analysis:

- Agricultural crop residues included corn stover, wheat straw, rice straw, and cotton stalks
- Other wastes included the organic fraction of municipal solid waste, urban tree residues, and construction and demolition wood
- Biogas includes landfill gas, digester gas, and sewage gas
- Sludge includes manure and bio-solids
- Energy crops included switchgrass, hybrid poplar, and willow

Figure 11: United States Available Biomass Supply Curve: Farm-Gate Cost per Dry Ton Versus Available Quantity



1. Agricultural crop residues include corn stover, wheat straw, rice straw, and cotton stalks.
2. Other wastes include the organic fraction of municipal solid waste, urban tree residues, and construction and demolition wood.
3. Biogas includes landfill gas, digester gas, and sewage gas. This analysis assumes all biogas is available at no cost and is used onsite.
4. Sludge includes manure and bio-solids. We assume that all sludge is free and used onsite.
5. Potential energy crops include switchgrass, hybrid poplar, and willow. Note that production was not evaluated above $50/dt.
6. A supply curve analysis was not done for traditional crops (corn, soybeans, and rapeseeds). Used the national average price and total quantity produced.

Source: Arthur D. Little analysis based on existing resource assessment studies; detailed references in the appendix to this report.

Therefore, searching for lower cost biomass will be important. First, there are likely to be scenarios in which feedstocks have a negative cost (i.e., the cost for alternative disposal methods is avoided, for example in the form of avoided tipping fees). Examples include urban tree residues and municipal solid waste. We expect that such resources will be used in early implementation of certain biomass projects. However, whenever commercial uses for such resources are found and a market for them is established, their cost will likely enter positive territory. So although sources of negative cost feedstock may currently provide for early entrant plants, in the high-penetration scenarios of interest to this study; these feedstocks are not likely to be available at negative cost.

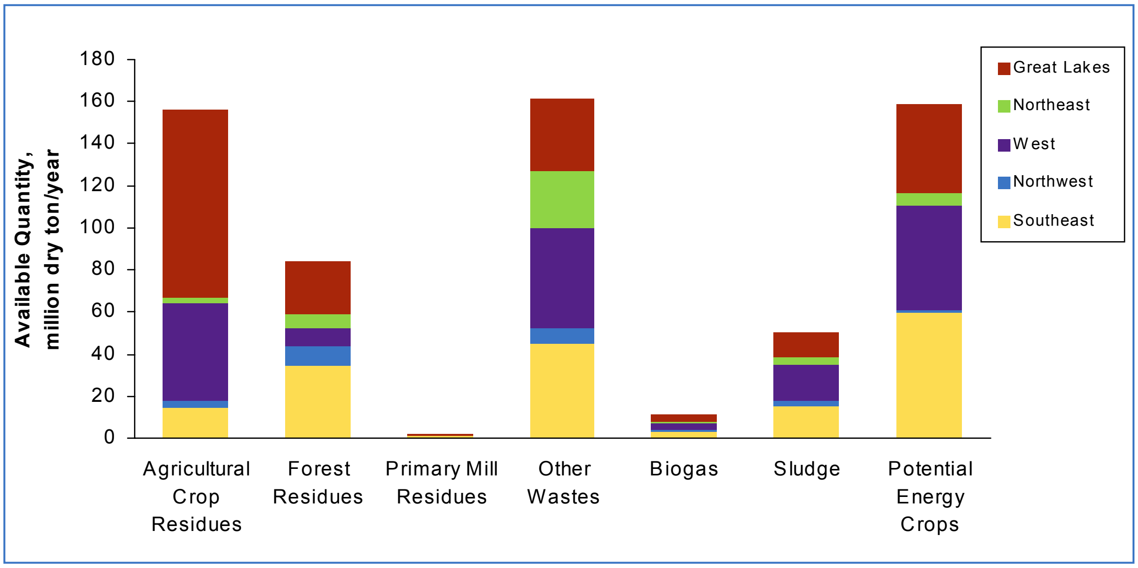
On the other hand, the projected supply curves are subject to change if a biomass resource becomes a widely traded commodity, similar to corn or soybeans. For example, agricultural crop residue available quantities could increase dramatically if residues are seen as having cash value to the farmer. Current agricultural production is optimized to minimize currently worthless residues. If such optimization were reversed, it is thought that production of residues could be increased by a factor of two (according to USDA). Because this would presumably allow more efficient residue collection, the cost of collection could be reduced. However, this may be partially offset by increased cost of producing the primary crop. Increased residue production of this sort was not considered in the quantitative analysis presented in this report.

The cumulative biomass resources (and the regions as defined by the Regional Biomass Energy Program) with the highest potential in the $0-40 per dry ton farm-gate price range are shown in Figure 12. These include but not limited to:

- Agricultural crop residues, such as corn stover
- Forest residues
- Other wastes such as organic municipal solid waste
- Energy crops such as switchgrass

(Figure 12 is an integration of Figure 11; the amounts shown are not associated with a single price point. Data from Figures 11 and 12 is in the appendix to this report.)

Figure 12: Cumulative United States Regional Available Quantities at 0 to 40 $/dry ton Farm-Gate. Available Quantity, Million Dry Ton per Year



Note: Regions defined by Regional Biomass Energy Program: Great Lakes region: MN, IA, WI, IL, IN, OH and MI; Northeast: New England, NY, PA, NJ, and DE; Northwest: WA, OR, ID, and MT; Southeast: MD, WV, VA, NC, SC, GA, FL, AL, MS, LA, AR, MO, KY, TN; West: CA, NV, WY, ND, SD, NE, KN, OK, TX, NM, CO, UT, AR; Data did not include Hawaii and Alaska

Source: Arthur D. Little analysis based on existing resource assessment studies

With careful management and state-of-the-art production and harvesting practices, the rich natural resources that allow for increased production of biomass for energy and product applications could be maintained or perhaps even improved in some cases. Converting traditional cropland into perennial energy crop production could yield net benefits in increased soil carbon and nutrients. Reduced runoff contamination and improved biodiversity are additional potential benefits. Marginal lands that are typically not in production today need to be carefully managed to realize net benefits from energy crop production, or at least to avoid damage to the soil, water, and ecosystem. If agricultural residue collection is managed properly, soil quality (e.g. organic matter, nutrients, and soil stability) can be maintained and/or improved and increased runoff contamination of waterways avoided. Forest residue collection must be managed properly to prevent erosion and damage to ecosystems and to realize benefits from fire prevention. The environmental impact of increased utilization of biomass is a continued topic of study and debate.

The studies underlying this report identified several aspects of biomass production that warrant additional research. The information currently available is based on smaller scale studies. As a result, the inter-regional consistency of the information is not sufficient to validate the results and determine landscape scale effects. Also, a better coverage of detailed regional data nationwide could aid investors in siting new projects and coordinating the establishment of new biomass feedstock markets. Finally, a more precise understanding of the total environmental benefits and impacts of biomass production (including air, ecosystem effects, water, soil, and others) would aid tremendously in better understanding the total impact of increased biomass production.

Options for Growth

The initial list of biomass to energy and product options for this report considered all options that were reported in the literature. However, after careful analysis of each of these options against a set of screening criteria, developed by Arthur D. Little with input from USDOE, many options were removed. This executive summary reports on the options selected. For a comprehensive review of the options considered and the screening analysis the reader is referred to the full presentation-style report. A high level summary of the screening criteria, options identified and the options that were removed for each category (e.g. biopower, biofuels and products) is included in the appendix of this text-style report.

This section of the report first addresses the technology classes that are applicable for the categories of biopower, biofuels, and bioproducts. Next, for each sector, the most attractive options are discussed along with the results of the economic screening analysis. Technologies are also identified that could further increase biomass utilization for power, fuels, and products in the post 2010 time period. We then used a scenario analysis to understand the implications of time-related issues for technology introduction. Two scenarios were developed: a business-as-usual and an aggressive implementation scenario. This section is then concluded with a discussion of the technology development needs that are required particularly for fuels and products applications. Finally, the implications for "Biorefineries" to reduce the project costs of biomass projects are examined.

Technology Categories

There are a number of technologies that are common for the applications of biopower, biofuels and bioproducts. Generally, biomass technologies used to produce power; fuels and chemicals can be classified into five categories:

- ***Physical separation***. The products or product components are recovered via simple physical separation processes (e.g. extraction, crystallization or distillation). Typically, only a modest fraction of the feedstock is useable for this purpose, so alternative uses must often be found for the residues (examples are fuel and power production). As a result, these processes are currently often integrated with food or pulp & paper production. Physical separation takes full advantage of the inherent structure of the biomass. An example of physical separation is the use of lipids with limited industrial product applications.
- ***Low temperature chemical processing***. Chemical processing (usually enzyme, acid, or base-catalyzed) is used to break the biomass into sub-species and then to recover product fractions from the resulting mixture. For the same reasons and with physical separation, low temperature chemical processing is often integrated with food, feed, or pulp & paper production. Examples include oil splitting/transesterification of lipids to form glycerol and fatty acids/esters/alcohols. Future examples may include

the use of cellulosic biomass to form levulinic acid, a possible future “bio-building-block”.

- ***Fermentation***. Conversion of the feedstock involves using microorganisms (or portions of microorganisms) to produce a product. Currently, most of these processes start with either starch or sugar as a feedstock. Often production is integrated with food and feed production (e.g. corn wet and dry mills). Aided by developments in biotechnology, fermentation technology is currently opening up new routes to monomers and polymers based on biomass, which could capture tremendous markets (in addition to fuel markets). The flexibility for feedstock use is currently limited compared to higher temperature, chemical treatment based processes. Biotechnology tools may lead to the design of new metabolic pathways for production of a wider variety of chemical species using a wider spectrum of feedstock.

- ***Pyrolysis processing***. Pyrolysis involves high-temperature thermal conversion of the feedstock in the absence of free oxygen to form a broad product slate, many of the products of which could be used as chemicals or possibly as fuels. Because of the broad product slate, ranging from hydrogen to char, co-production of a multitude of products as well as either fuels or power is unavoidable if not essential. Because of the processing operating window, a wide range of feedstocks from starch crops to cellulosics can be utilized. Processing considerations coupled with the properties of the feedstock usually dictate the type of feedstock used (e.g. woody versus grassy feedstocks).

- ***Gasification and Combustion.*** Gasification and combustion involve complete breakdown of the feedstock. In the case of gasification a synthesis gas is produced (primarily carbon monoxide and hydrogen) which can be converted to a wide range of fuels and products. Although this technology provides a large degree of flexibility with respect to the feedstock choice and product slate; it does not leverage the structure inherent in the biomass at all. As such, producing chemical products from biomass through this route face challenging competition from products made from simpler feedstocks through C_1 chemistry, and from other fuels in the case of power production.

In general, for commodity markets, scale of production (economy of scale effects) associated capital cost, feedstock cost (including delivery costs), and nonfuel-operating costs are major issues of technology performance across all three sectors.

Biopower Options for Growth

From an initial list of over fifty options, four classes of biopower technologies that include both short-term and long-term options to increase significantly the use of biomass were selected.

Selected Options and Cost Comparison

The economic result of the screening is summarized in Figure 13, which will be discussed in the following paragraphs. The biopower screening analysis has yielded the following findings:

- Utilization of gaseous biomass (e.g. biogas) represents a modest market potential but provides an economically attractive option that could be developed with low financial and technical risk[17]. Biogas could be used for both grid-based and onsite power applications. Where feasible, biogas options are cost-competitive today. Biogas is attractive because it represents a very low-cost but high-quality feedstock.
- Co-firing of biomass with coal or natural gas represents grid power options that leverage existing invested capital and capacity. The economics of co-firing solid biomass and gasified biomass with fossil fuels are nearly competitive with wholesale power but typically not with the marginal cost of coal-based power. Both of these short to mid-term options are commercially available today or can be made available within 1-2 years with minimal technology demonstration.
- Refuse derived fuel (RDF) gasification represents a longer-term option. The feedstock is available at low cost and the economics are projected to be attractive. Since a small fraction (less than 15 percent) of municipal waste is converted for energy today (in waste-to-energy plants), there exists a very large untapped market potential. Technology development and demonstrations are required along with addressing the hurdles for implementation (e.g. NIMBY issues).
- For onsite power, a mid-to-long-term option with significant potential is gasification of process wastes, in particular repowering black liquor and hog fuel/bark boilers in the pulp & paper industry with gasification technology. Where onsite waste fuels are available (zero cost or negative cost), gasification technology could be cost competitive, have modest market impact, and provide environmental benefits. In existing plant gasification would provide significant improvements in efficiency, and in some cases may provide additional process benefits. The all-in cost of biomass integrated gasification combined cycle (IGCC) power for sale into the wholesale market is expected to be above the cost of competing conventional technologies (e.g. coal-based and natural gas GTCC), but represents an enormous long-term opportunity. Even so, some significant technical and non-technical hurdles must be overcome by each of these technologies. As the largest user by far of biomass-for-energy, the pulp and paper industry is expected to be critical for the long-term success of increased energy production from biomass process residues, and potentially for stand-alone biomass power, because of its existing biomass supply infrastructure.

[17] Because of the market complexities; the biopower analysis used three base cases to evaluate the economic competitiveness of biopower technology options. Grid applications were compared to the levelized cost of new capacity natural gas combined cycle (GTCC); the marginal cost of coal-based power (if applicable); and grid baseload power (if applicable). Onsite power applications were compared to the projected prices for industrial sector electricity from the EIA 2001 Energy Outlook, 2010 reference case. We used the projected prices for fossil fuels (natural gas and coal) from the EIA Outlook, 2010 reference case.

- Biopower has the potential to be cost effective at a variety of scales, ranging from less than 1 MW to 100 MW, depending on the application and technology used. This provides the opportunity to utilize feedstocks that might not be useable otherwise for biofuels or bioproducts, each of which will require large amounts of biomass to achieve the necessary economy of scale. In addition, biopower is likely to be part of some other biomass conversion facilities, or indeed bio-refineries, to utilize their residue for useful products.

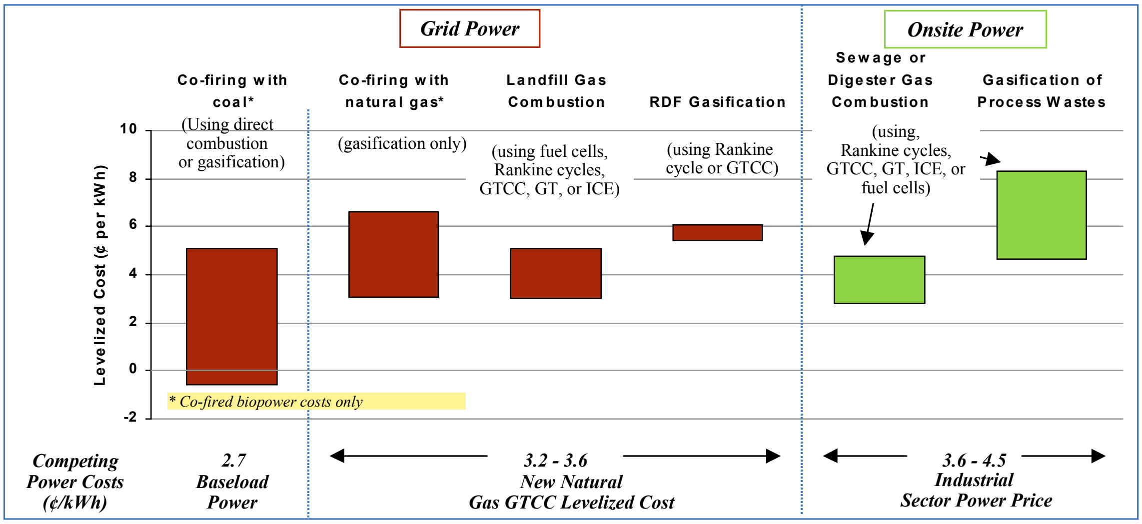
Several opportunities for biopower are significant and could independently achieve the aggressive implementation goal for biomass use if fully exploited. Even though it is unlikely that any one application will achieve its full technical potential by 2010, a combination of applications could meet the aggressive goals for biomass use. Biopower utilizes a variety of feedstocks that allow for this type of parallel deployment with minimal inter-application competition.

Figure 13 provides a summary of the most promising biopower options compared to a relevant competing technology. The costs shown are based on the levelized (all-in) cost of electricity. Three different baseline power generation rates were used for comparison:

- For grid power applications, co-firing of biomass with coal was compared to an estimated cost of grid baseload power.
- All other grid power options were compared to the cost of new capacity natural gas combined cycle plants.
- Industrial or onsite power options were compared to the average price of industrial sector power from the EIA 2001 Annual Energy Outlook projections for 2010, reference case.

The costs shown are total fuel chain costs that include the cost of the biomass fuel; delivery costs for the biomass fuel to the power plant, and power generation costs. The energy losses of transmission and distribution are included for grid applications but not the actual electricity delivery costs. The bands in each category reflect feedstock cost range and/or technology type used for power generation.

Figure 13: Summary of Levelized (All-in) Costs for Attractive Biopower Options (¢ per kWh)



Note: The costs represent full fuel chain cost of electricity. For co-firing cases, biomass is co-fired at a rate of 10 percent based on heating value using RDF, corn stover, woody biomass, wheat straw, corn stover or switchgrass. The band in the co-firing case is the effect of feedstock used. Natural gas is assumed to cost $2.90-3.47/MSCF. The analysis includes transmission and distribution energy losses of 7.2 percent for the grid power options, but not the actual electricity delivery costs. Biogas and landfill gas are assumed to range in price from 0-0.50 $/GJ; RDF and process wastes from $0-10/ton; conventional biomass (e.g. corn stover, wheat straw, switchgrass, and woody biomass) from $30-60/ton.
Source: Arthur D. Little analysis

Benefits and Impacts of Biopower

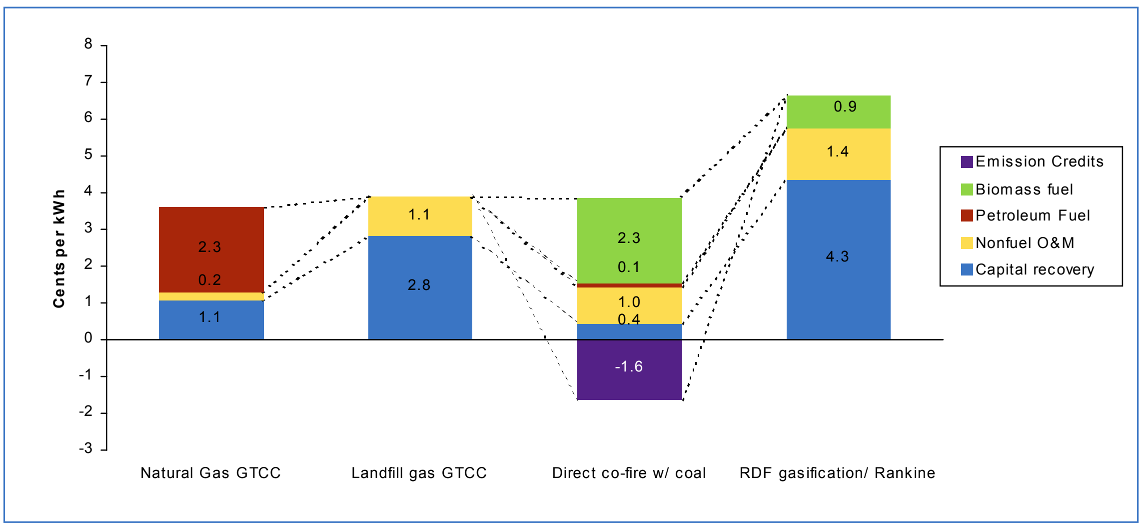
Biomass co-firing has the potential to significantly reduce NO_x emissions from coal plants, in addition to SO_x reductions. These reductions were included in the levelized cost of electricity in the form of emission credits. Co-firing biomass in a natural gas GTCC does not produce NO_x and SO_x emission savings, so emissions credits were not included. The biomass co-firing options include the costs for the biopower implementation only (e.g. incremental capital cost, incremental operating cost, and cost of the biomass fuel; the existing plant is considered fully depreciated and coal or natural gas fuel not included). The main environmental impact of the use of biopower is expected be 26 to 80 million MT per year reduction in CO_2 emissions.

Co-firing options appear the most attractive, due to low capital costs and in the case of coal, emissions credits. Landfill gas and other biogas options appear to fall in the 3-5 ¢/kWh range, driven in part by low fuel costs.

For grid-sited power plants using solid biomass feedstocks, the cost of the biomass feedstock is an important component of total levelized cost. The range in levelized cost of electricity is from slightly negative for RDF and sewage sludge co-firing (with coal) (¢-0.6 to ¢0.8/kWh) to approximately 7-11 ¢/kWh for biomass only power for grid applications using conventional biomass[18] (with costs of $30-60/dry ton farm-gate, which is not shown on Figure 13). Although today some residues may have negative cost, for this analysis the minimum cost is assumed to be zero, a general assumption made throughout the study, consistent with the concept that as biomass utilization increases, residues that were once thought of as liabilities now have market value.

Figure 14 shows examples of the cost structure for some of the attractive biopower options. As seen for landfill gas with gas turbine combined cycle, zero cost of the gaseous biomass fuel enables competitiveness with new capacity natural gas combined cycle. For biomass co-firing with coal, the bulk of the cost electricity is in the cost of the biomass feedstock. RDF gasification with Rankine cycle cost of electricity is highly dependent upon the capital cost for power even with a low-cost feedstock.

Figure 14: Examples of the Fuel Chain Cost Structure for Attractive Biopower Generation Options



Note: The costs represent full fuel chain cost of electricity. For co-firing cases, biomass is co-fired at a rate of 10 percent based on heating value; a biomass price of $30/dry ton farm-gate was used for co-firing case. Natural gas is assumed to cost $3.47/MSCF. Landfill gas was used onsite and considered zero cost. RDF was considered to be used onsite and had a cost of $10/dry ton. The analysis includes transmission and distribution energy losses of 7.2 percent for the grid power options, but not the actual electricity delivery costs.

Source: Arthur D. Little analysis

For some industries, most notably pulp & paper, residues are utilized for power and heat regardless of the power economics, because their use is integral to the industrial process. The gasification of black liquor and other biomass residues in that industry could double the efficiency of power generation. Interestingly, although this significantly aids the economics of the process, drivers for the technology development also include improved safety and reduced footprint. Finally, the pulp & paper industry also has the potential to exploit its biomass supply infrastructure to generate additional power for export, if the

[18] Conventional biomass in this study includes corn stover, wheat straw, switchgrass, and woody biomass such as poplar

economics are favorable and the added biomass utilization does not adversely affect its core business. As such, this industry would effectively become the host of independent biomass power projects, benefiting from the existing infrastructure it already has. Its impact is represented and considered as such in this study.

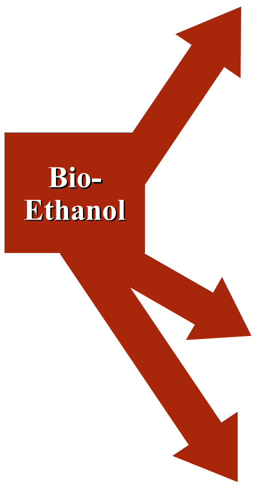
Biofuel Options for Growth

Selection and Cost Analysis

Bioethanol was identified as the most attractive biofuel option, from a list of over one hundred biomass-derived fuel chains. All biofuels analyzed are expected to be significantly more expensive to produce than petroleum fuels on an energy basis (e.g. dollars per million BTU energy content). Bioethanol offers several considerable advantages, and can be used in large quantities within the existing fuel infrastructure and markets with only modest modifications to the infrastructure and vehicles. Bio-FT diesel and biodiesel could benefit from the same benefits (at least at low-level blends), but are expected to have considerably higher prices (both in short and long term), though application at a limited scale may be appropriate. Other renewable biomass-derived fuels including synthetic natural gas, dimethyl ether, hydrogen, methanol, and biodiesel from seed oils face higher hurdles for implementation because of infrastructure investments required for broad use. A complete discussion of the biofuels screening analysis can be found in the full study report.

Bioethanol can be used in a number of ways as indicated in Figure 15. The most value-added bioethanol application is its use as an oxygenate additive for reformulated gasoline. Its value could be approximately the same as other oxygenate additives (on a volume basis) such as MTBE (Methyl Tertiary Butyl Ether), or about twice ethanol’s energy value (e.g. dollars per million BTU, fuel value). The recent debates around MTBE have considerably increased the uncertainty surrounding MTBE specifically, and oxygenate mandates for gasoline in general. Other uses of bioethanol (e.g. as octane booster; low sulfur, low aromatic and volume extender blend stock; and as a neat fuel) receive lower market values and thus face higher barriers to market penetration.

Figure 15: Potential Uses of Bioethanol as a Fuel



Gasoline Additive or Blend Market (Primary existing market with significant potential for near-term expansion)

- Current regulations limit blends to 10 percent by volume ethanol
- Higher concentration ethanol blends (likely up to 20%) are technically feasible
- Blended at 5 to 10% in gasoline by volume (typically 5.7, 7.7, 10%*)
- Works in conventional vehicles without any adjustments
- Provides octane improvement, emissions reduction, a near-zero sulfur blend stock

Conventional Gasoline

- Ethanol value based on gasoline price with a premium based on ethanol's octane value
- Historically, ethanol was used as an octane enhancer and gasoline extender
- Suboctane gasoline for ethanol blending is now being produced in areas with high ethanol use
- E10 has an RVP waiver to compensate for its RVP increase

Reformulated Gasoline (RFG) and Oxygenated Gasoline

- Clean Air Act requires a minimum oxygen content (Primary oxygenates are ethanol and MTBE; public acceptability of use of ethanol as ETBE is questionable)
- Value is based on oxygenate content (based on MTBE); minimum is based on competing MTBE prices
- Ethanol market will likely expand with an extended MTBE ban and continuation of oxygenate use in RFG
- Higher premium is possible if MTBE is phased-out suddenly resulting in an effective ethanol mandate
- Requires adjustment of summer RFG gasoline blend stocks to produce low vapor pressure gasoline
- May require more gasoline blend-stock; and may put more pressure on gasoline supply

Neat fuel (Existing, small market with largest potential size; least potential for expansion in near to mid term)

- Denatured with gasoline (e.g. Ed-85 in U.S.; Ed-95 in Europe); requires modest modifications to some vehicles, though new vehicles sold in the U.S. are increasingly fuel flexible, requires slightly increased maintenance
- Receives no premium over super premium gasoline (value based on heat content)s

E-diesel

- Ethanol may also be used as a diesel oxygenate in e- diesel or oxydiesel (~10% vol ethanol; 5-10% other additives)

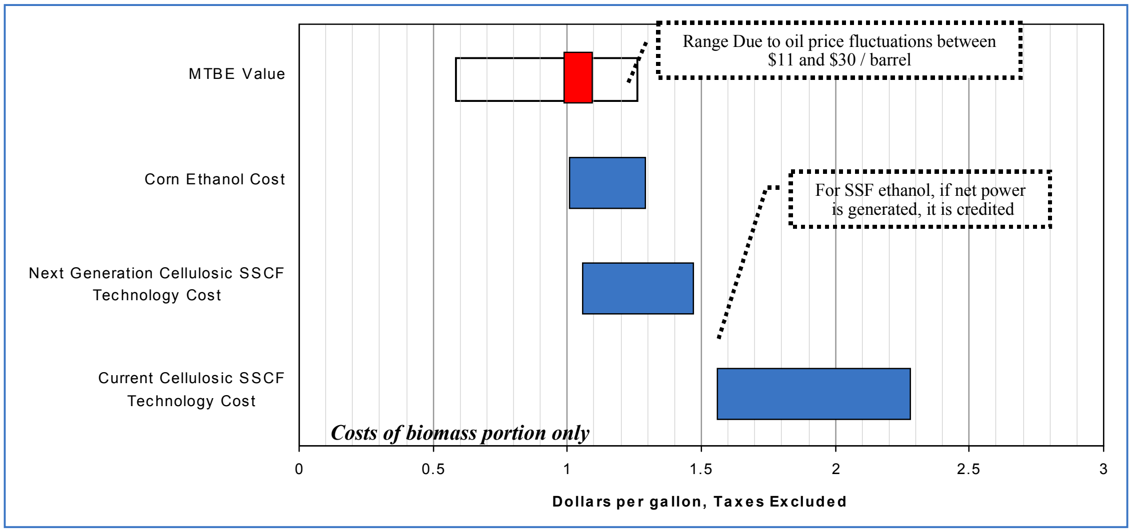
*5.7% and 7.7%vol are blends that correspond to the oxygen content standards for gasoline sold in ozone nonattainment and carbon monoxide nonattainment areas under the CAAA. Higher volume percentages needed for MTBE

Source: Arthur D. Little analysis

Currently the production cost of bioethanol, produced mainly in corn mills, can be competitive with alternative oxygenates under most oil price scenarios when the ethanol fuel tax credit (of about $0.54 per gallon ethanol) is applied. Provided oxygenate standards for reformulated gasoline are continued, the oxygenate market could be a tremendous continued opportunity for bioethanol. However, in the foreseeable future, and at least until 2010, continuation of the ethanol tax credit will be needed to support continued growth in ethanol use, given current oil price projections.

However, to significantly increase bioethanol use as a fuel, two key limitations of current bioethanol technology must be overcome. First the current corn-based technology requires co-production of a wide range of other products to achieve the current cost levels. This means that growth of bioethanol production would also require growth in the sale of the other products, which feed into large (though not compared to fuels) but limited markets. Second, the potential for further cost reduction is limited because of the high cost of the corn feedstock. This would effectively require a significant increase in the ethanol yield from corn. Figure 16 summarizes the fuel chain costs for blended additives for the biomass fuel only

Figure 16: Competitiveness of Bioethanol with MTBE as an Oxygenate Additive in Reformulated Gasoline, $ per Gallon (Taxes Excluded)



Note: The bar range represents the spread of feed stock cost (conventional biomass from $30-60/ton). Corn ethanol price is based on ($1.5/bu with 2.8 gal ethanol yield per bushel corn) to ($2.9 per dry bushel corn with 2.7 gal ethanol per bushel); total chain cost. The blended fuels are blended at a level of 10 percent by volume. The costs represented are for the biomass-derived fuel portion. The bar range of the SSCF options reflects feedstock cost of $30 to 60 per dry ton; farm-gate. SSCF is simultaneous saccharification and co-fermentation technology that utilizes cellulosics as the feedstock.

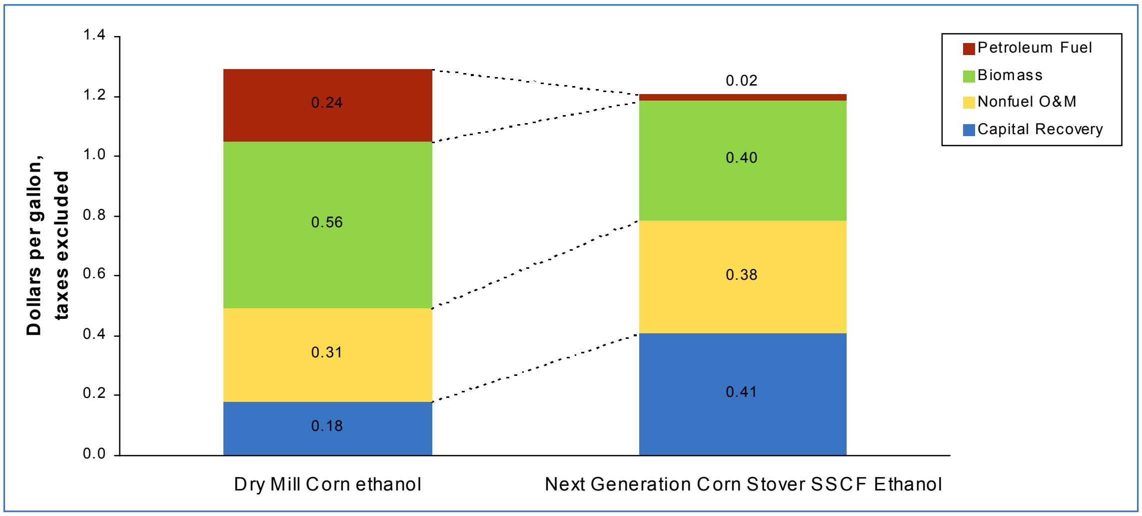
Source: Arthur D. Little analysis

Ethanol technology that can utilize cellulosic feedstocks is expected to provide an alternative with large market potential and larger cost reduction possibilities. One key feature of cellulosic technology is a smaller slate of co-products (primarily power). As shown in Figure 16, even the earlier generations of the technology could bring the cost of cellulosics-based ethanol on par with current corn-based ethanol, but without requiring sale of co-products (perhaps some power). Until 2010 this technology is still expected to require the ethanol tax credit to compete in additive and blend-stock markets.

In the meantime, there is opportunity for additional corn-based ethanol production, but also for "niche" applications of first-generation cellulosic bioethanol technology, for example based on waste fuels or on using the infrastructure from existing or idled biopower plants or pulp & paper mills.

Figure 17 shows examples of the cost structure for some of the attractive biofuel options. For both corn-based and cellulosic ethanol, feedstock cost is a large portion of the cost (using a cellulosic biomass farm-gate cost of $30/ton and corn price of $2.9/dry bushel). For cellulosic ethanol, further cost reductions in capital and operating cost will enable broader market applications. Even with a zero cost feedstocks, the cost of ethanol approaches under $0.80 per gallon.

Figure 17: Examples of the Cost Structure for Attractive Biofuel Options (Taxes Excluded)



The costs represent full fuel chain cost of fuels Biomass feed stock cost used is $30 per dry ton. Corn ethanol price is based on $2.9 per dry bushel corn. The gasoline and diesel prices are based on a $21.4 per barrel crude oil price that is the reference oil price in 2010 in the EIA 2001 Energy Outlook. The prices do not include state or federal taxes. The SSCF ethanol fuel costs are proportioned by energy value. Cases using poplar and wheat straw have power export.
Source: Arthur D. Little analysis

Benefits and Impacts of Biofuel

The main environmental impacts of the use of bioethanol are expected be 5 to 14 million metric ton per year reduction in CO_2 emissions and a reduction in groundwater contamination. In addition, a reduction in SOx emissions will result, although this reduction is significantly reduced due to tightening standards on conventional petroleum-based fuels. Other air pollution benefits will be modest. In oxygenate applications, ethanol would replace MTBE, which has similar emissions impact (though the magnitude of the benefit is debated). In other blending applications, ethanol may have some modest benefits in terms of NO_x emissions, but may actually increase volatile organic compound emissions, because of its high vapor pressure. For neat fuel applications, modified engines will be generally required and any NO_x emissions benefits will likely be traded off against engine performance to meet but not exceed emissions regulations (as is typically done with all engines).

Perhaps one of the clearest environmental benefits of ethanol in oxygenate markets is the reduced pollution of groundwater. Currently groundwater pollution with MTBE, a known carcinogen, is a major concern in areas that have RFG oxygenate requirements. Ethanol is far less harmful than MTBE (not a carcinogen, and not very toxic) and, more importantly, is readily biodegradable. This benefit is already a driver for ethanol growth.

Increases in biofuel market penetration before 2010 are expected in bioethanol. Despite the attractiveness of bioethanol, achieving 800 million to 2 billion gallons per year of additional bioethanol production and consumption would cost the nation around $420 to $1300 million by 2010, most of which would be the cost of the tax credit (not counting the increase of the biofuel baseline of ~300 million gallons by 2010). Part of this added cost would be off-set by added tax revenues to the extent that bioethanol offsets MTBE derived from methanol that is produced increasingly overseas.

Bioproduct Options for Growth

Bioproducts represent high-value opportunities for the use of biomass feedstocks, as the product value can in some cases build on unique characteristics of the biomass feedstock, rather than just on its energy content. We identified over eighty products within the scope of the report that can be made from biomass. Some of the products can be produced as single products, such as many of the fermentation-based products, while others are produced in processes that inherently co-produce other chemicals (e.g. pyrolysis processes), fuels (e.g. FT-naphtha), or food products.

The technology necessary to produce chemicals from biomass can be more complex than that required for fuel and power production because of stricter purity and performance requirements imposed by some of the applications. The products that could be produced from biomass can be categorized into four categories:

- ***Lipid based products*** (e.g. fatty acids, alcohols, esters) derived from fats and seed-oils. Although lipids do not offer the largest possible market potential (compared to some polymers), the technology is available now and could eventually produce cost-competitive products.
- ***New "biomonomers"*** produced from sugars or starch via fermentation. Significant industrial interest has arisen in their development and potential (e.g. Cargill-Dow LLC and E. I. Du Pont de Nemours). Chemical entities currently targeted for production from biomass in this category include lactic acid and 1,3-propanediol, each of which can be used as a polymer building block. The cost of producing these chemicals is expected to become competitive with that of their petroleum-based analogs. Lipids are also a source of bio-monomers through advances in "functionalizing" the oils for specific properties.
- ***Pyrolysis processes*** to produce phenolics, and possibly some niche chemicals, from wood or wood-waste, has the potential to make competitive products for medium size market applications. For example, phenolics may be cost-competitive with petroleum-based phenolics for phenol-formaldehyde adhesive applications based on technology that is available currently.
- ***Syngas based products*** (e.g., FT-naphtha, methanol) appears too capital intensive to compete with much larger-scale natural gas-based alternatives on a stand-alone basis. Hence we do not see it as one of the most attractive options for stand-alone chemical applications. However, if its use for fuel production (notably diesel) would justify the production of synthesis gas, the potential impact of the naphtha co-product in chemical applications would be considerable, and implementation would be straightforward.

Many of the products identified are fine or specialty chemicals with modest potential markets. However, in order for chemicals to have a significant impact (environmental and/or rural economic), they should be targeted at higher-volume markets such as polymers or commodity chemicals. Products with such potential were all included into our analysis. The markets for bioproducts are numerous. Some examples of markets for bioproducts both today and in the future are listed in Figure 18.

Figure 18: Examples of Markets and Applications for Bioproducts

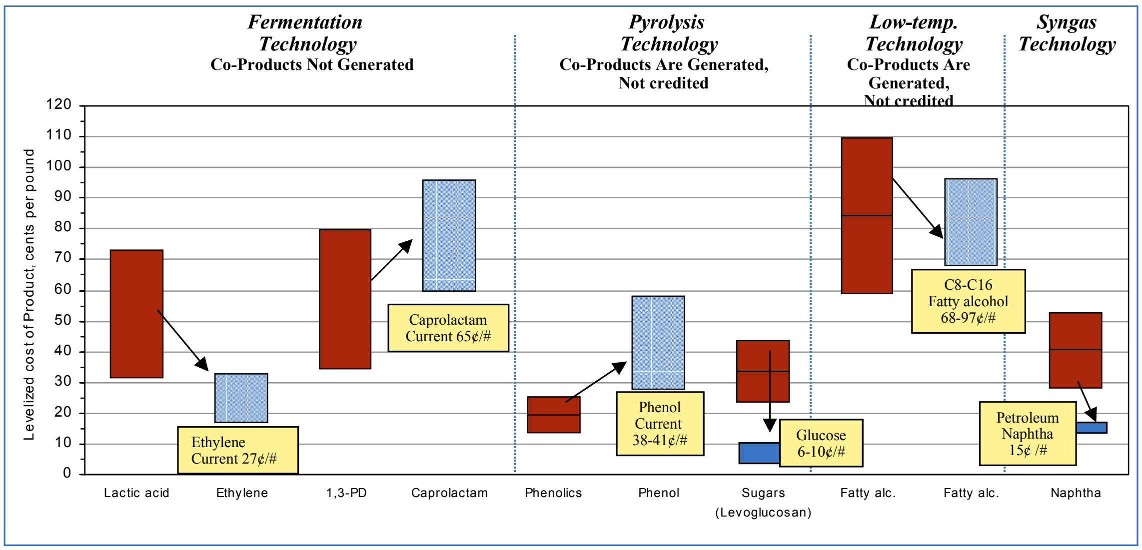
Functionalized Monomers for Polymers	Functionalized monomers for high volume polymer applications include lactic acid, 1,3-propanediol, and succinic acid using fermentation technology. Lipids based on plant oils and animal fats can be used (with chemical modification) to produce polyols for urethanes for rigid and flexible foam applications. Urethanes for CASE (coatings, adhesives, sealants, and elastomers) applications are also being developed
Solvents/ Cleaning Agents	Fermentation based solvents such as lactate esters and lipid based solvents such as methyl esters are being piloted and demonstrated as halogen free, biodegradable, low-toxic alternatives to conventionally used solvents. Wood and citrus terpenes also find use as cleaning agents and solvents
Lubricants & Surfactants	Lipid based products (fatty acids and their derivatives) are being piloted and demonstrated for this application. There has been activity combining genetic engineering and processing to produce seed oils for application in the markets of hydraulic fluids, engine oils, penetrating oils, & cutting fluids. Genetic engineering is being used to "design" the carbon number product spectrum of the vegetable base oil
Inks/Paints	Soy based inks have already found application in this area.
Specialty Chemicals	Work is continuing to develop low cost routes to produce antifreeze replacements for petroleum derived ethylene glycol. Propylene glycol could be produced by a number of routes using fermentation and subsequent conventional chemical conversion technologies. Routes which produce ethylene (for ethylene glycol among other derivatives) and propylene glycol from thermochemical conversion of C_6 and C_5 sugars
Composite Applications	Biomass materials such as plant fibers have historically found use as fillers and fiber material for material such as concrete-based products. Work is continuing on finding new applications as fillers and/or fibers for thermoset applications particularly for automotive applications and less demanding commodity applications.

Source: Arthur D. Little analysis

Compared to biopower and some biofuels, many bioproducts may provide clearly different and better performance and functionality than their conventional counterparts. This could increase their attractiveness and stimulate their commercialization. On the other hand, they will not be completely fungible with conventional products. Commercialization of bioproducts may therefore require several steps of development beyond the process technology development effort. Bioproducts that can serve as "drop-in" replacements may use existing infrastructure such as distribution and marketing channels with the associated investment savings. It is likely that "drop-in" replacement applications will be limited, therefore additional investments may be required for application and market development. We did take this into consideration when evaluating the required development times for the bioproducts value chains, but we did not explicitly include it in the cost consideration, given the status of the development of these products.

For this study, the costs include those associated with making the primary product up to the primary processing plant gate where a first comparison can be made with conventional chemical products. All downstream derivative production, fine chemical formulation, product manufacturing, and production distribution and marketing are not included. Therefore, any differences in product properties could improve or worsen the competitiveness of the bioproduct. Figure 19 summarizes the estimated primary plant gate levelized cost of production for examples of promising bioproduct options assuming green-field plants.

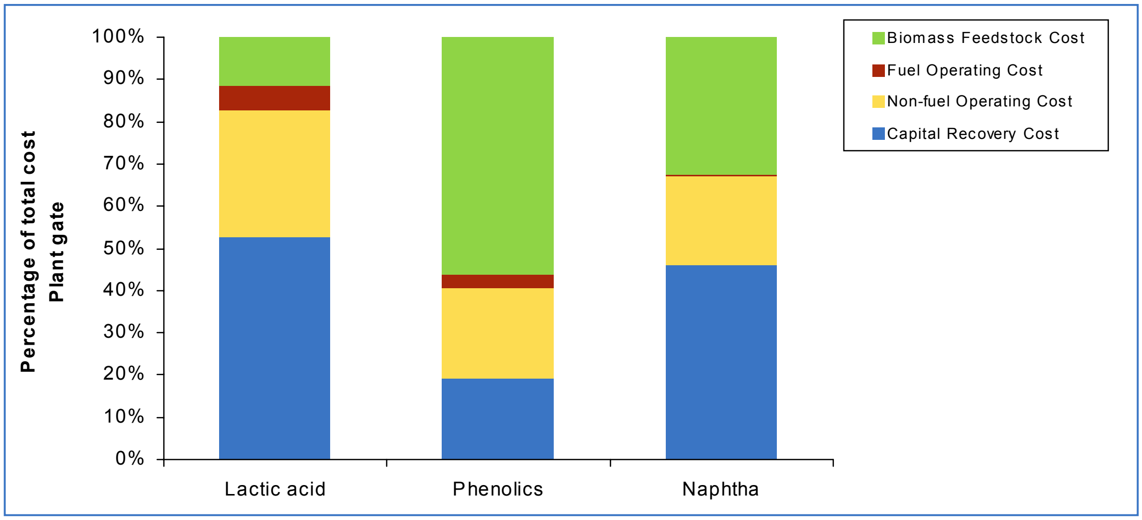
Figure 19: Primary Plant Gate Levelized Cost of Products, Cents per pound, Co-products Not Credited



Note: The price of corn was $2.92 per dry bushel. Wood for phenolics and levoglucosan is $50 per dry ton. Seed oil is $0.17 per pound. Cellulosics were $30 per ton. Assumes green-field plants and did not address scenarios involving retrofit of existing process equipment
Source: Arthur D. Little analysis

Despite the current use of relatively costly feedstocks (seed oils and sugar feedstocks), this is not always the dominant cost factor as it is in current biopower and biofuels technology. Capital and non-fuel operating and maintenance (O&M) appear significant as well, particularly for fermentation-based products. Figure 20 shows examples of the cost structure for options that were considered in the economic screening analysis.

Figure 20: Examples of Product Cost Structure Up to the Primary Plant



Note: The price of corn was $2.92 per dry bushel. Wood for phenolics is $50 per dry ton. Seed oil is $0.17 per pound. Cellulosics were $30 per ton. Assumes green-field plants and did not address scenarios involving retrofit of existing process equipment
Source: Arthur D. Little analysis

The key conclusions from the option analysis for bioproducts are that:

- Fermentation processing for “biomonomers” appears promising in the near–midterm provided that large-scale continuous processing can be achieved that delivers cost savings from economy of scale.
- Pyrolysis technology may be used to produce niche products cost effectively (even at an advantage compared to petrochemicals today). Additional costs may accrue from investments in product application & market development.
- Low temperature processes, such as oil splitting, are currently attractive but they are mature and expansion is likely to be limited due to raw material availability and limited demand for glycerol co-product.
- Syngas processes based on biomass are likely to be too capital intensive for broad application on a stand-alone basis even though it promises high flexibility towards the product slate. The cost of gasification and reforming to produce the synthesis gas alone makes it prohibitive. It is conceivable that if large-scale gasification technology is implemented for either power or fuels production, a marginal addition to produce bio-products would be value adding.

Scenario Analysis

A scenario analysis was used to evaluate the potential magnitude of the impact of increased biomass use as a function of time and as a function of support for biomass. The scenarios describe a combination of external factors that influence the development of the biomass-to-energy and –products industry. The Business As Usual (BAU) scenario describes a situation where government support for biomass is unchanged (from the 2000 situation) while the Aggressive Growth scenario describes the situation in which acceleration of biomass use is essentially maximized. Basic economic factors, such as economic growth and energy prices, were assumed to be the same in both scenarios. Figure 21 summarizes the general assumptions made in developing the scenarios for increased deployment of biopower, biofuels, and bioproducts.

Figure 21: General Assumptions for Business as Usual and Aggressive Growth Scenarios

Business as Usual (BAU)	• No special actions are taken • Successful technology development and rates of progress are consistent with best-in-class performance • Policy instruments currently in place will continue to be in place in the future
Aggressive Growth	• Biomass Use Triples by 2020 • Aggressive or accelerated: – Technology and application development progress rates – Technology performance – Market acceptance of and market pull for products – Market penetration rates necessary are achievable

Source: Arthur D. Little analysis

Implementing these options will take time, and will require the right actions to be taken in a timely manner, due to various factors, including:

- Time required for the technology development process
- Time required for application and market development
- Market barriers
- Implementation of necessary policy actions

Technologies are assumed to mainly capture growth markets, rather than replacement (exceptions are black liquor gasification, biomass co-firing, and oxygenate fuel blend stocks). The two scenarios were developed in different ways. The BAU scenario was developed by projecting increases in biomass use forward, starting from the year 2001. In the Aggressive Growth scenario we first developed a vision for the status of biomass use in 2020, and then working back to the current situation to define what would be needed to achieve the end state. The end state vision for biomass-derived power, fuels, and products is shown in Figure 22.

Figure 22: 2020 Vision for Aggressive Deployment of Biomass for Fuels, Power, and Products

2020 Vision

Biomass co-firing with coal fully exploited at a variety of scales and firing percentages, 10-15,000 MW co-firing in operation

Common technologies between utility-scale IGCC are transferred to P&P industry for hogged fuel and bark residues

Gasification-based technology is scale independent and low cost

RDF gasification fully accepted as viable option - commercially viable

Medium-scale gasification-based technology integrated with blending terminals

2 Demo FT-Diesel plants

FT Diesel demonstrated as low sulfur blending agent

LFG fully exploited - 3,000 MW added

Color Key

Biomass Co-firing with coal	Regulations & Biomass markets
Gasification/IGCC	Small-scale Gasification
LFG / biogas	Fermentation Technology
Power in P&P	Bio-Product Developments

5-6000 MW added in P&P through efficiency gains from gasification (black liquor, hogged fuel, bark, sludge).
(Capacity added via increased biomass utilization for power only, which is part of the 2020 Vision of the pulp & paper industry, would be in addition to this amount).

Common technologies between LFG, biogas and other applications are transferred across market segments. Technology developments are applicable to biomass fuels and products applications

- Small-scale power generation
- Gas cleanup
- Low-medium BTU combustion systems
- Project development learning and business models (e.g., for many small-scale sites)
- Partnerships

- Biomass infrastructure developed to deliver large quantities of biomass (energy crops, residues)
- Large companies involved
- JVs between fuel marketers and agro-companies
- Market mechanisms in place similar to other fuels (e.g., futures, B2B)

Onsite Conversion technology is scale independent and low cost

Residues used for highest value application

- Fuel specs require ultra-clean transportation fuels
  - Ultra-low sulfur
  - Low aromatics
  - Oxygenate requirement for diesel and gasoline
- Bio-blend-stocks receive preference over petroleum derived ones
- Green fuel premium is available for neat fuels in niche urban and fleet markets
- Alternative fuel status and tax credits are extended to other bio-derived fuels other than ethanol

- Bio-Products are seen as “Green” with enhanced properties that can carry a price premium
- Bio-Products will compete with petroleum products that are biodegradable which is also viewed as “Green”
- EPC industry has developed a new market, construction and operation of large scale bio-processing plants

Cellulosic ethanol primarily used in blending for octane enhancement and oxygenate content

Greater than 750 million gallons of cellulosic ethanol

At least 10 plants in operation using cellulosic feedstocks

Medium-scale conversion technology integrated with blending terminals

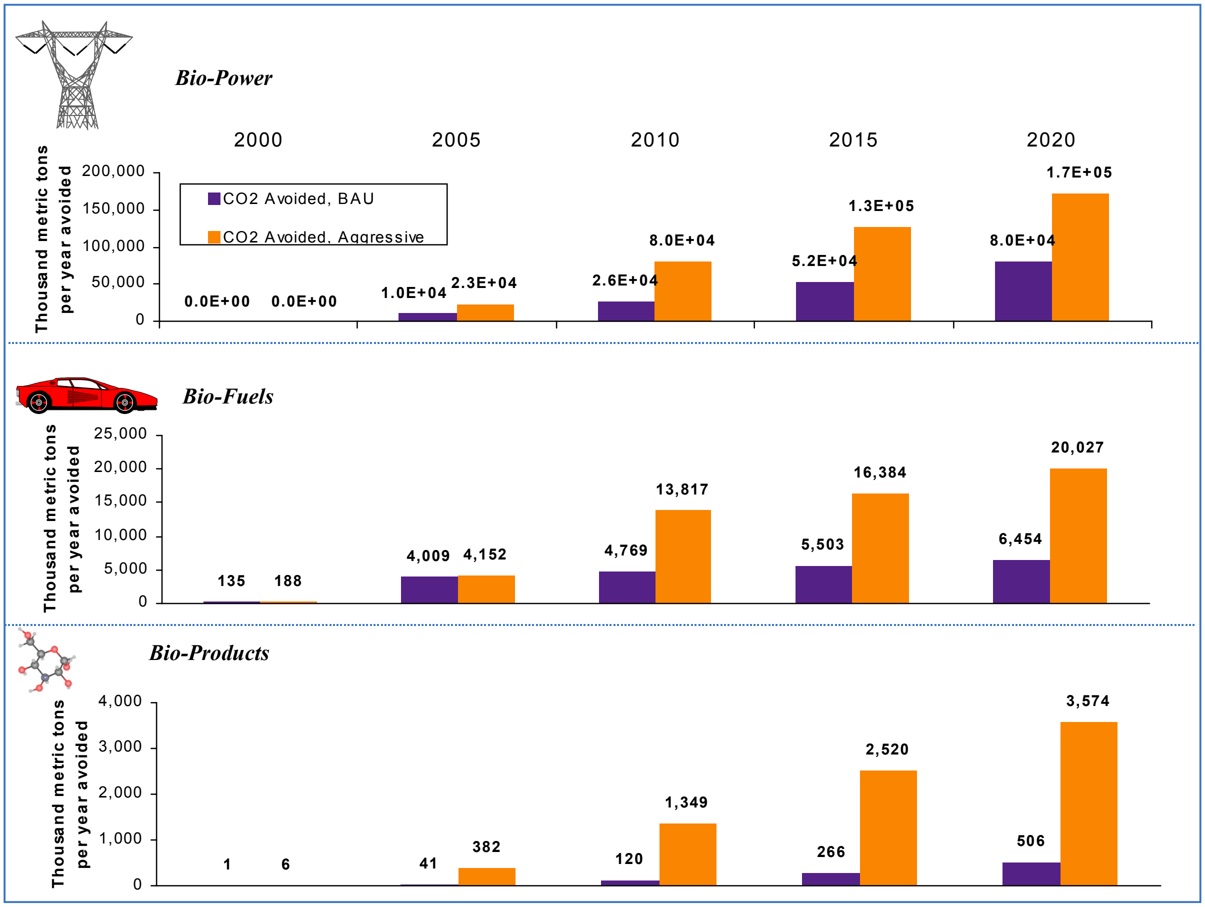
Conversion technology is scale independent and low cost

- An incremental 20 billion pounds of material derived from biomass is being produced per year in 2020. Most of the new capacity will leverage fermentation technologies. Growth will continue to leverage existing and new uses for ag products such as seed oils. High temperature processes using cellulosics make specialty products for small to medium volume applications.
- The consumers drive the demand for products seen as green.
- The processing technology for bio-products has been significantly improved and seen as clean. Biomass plants are no longer viewed similar to a MSW incineration plant.

Products are:
Solvents
Polymers
Propane diol polyester
Lactic acid
Other organic acids such as citric, succinic
Paints & inks
Detergents
Specialty Chemicals
Adhesives/Sealants/Coatings
Polyurethane intermediates (polyol)

Source: Arthur D. Little analysisAs a part of the scenario analysis, we evaluated the environmental benefit potential for each category. Biopower, biofuels and bioproduct industries are likely to provide considerable environmental benefits. These benefits could span all key environmental performance factors but the main benefits would be in reduced greenhouse gas emissions. Figure 23 below summarizes the carbon dioxide reduction benefits for implementing a business as usual (BAU) and aggressive deployment scenario for biopower, fuels and products. These are the same scenarios discussed in the “Options for Growth and Scenario Analysis” section.

Figure 23: Cumulative Carbon Dioxide Avoided for Business as Usual and Aggressive Implementation of Biopower, Fuels, and Products, Thousand tons per year avoided



Note: Cumulative carbon dioxide avoided as a result of proposed deployment of a business as usual and aggressive.
Source: Arthur D. Little analysis

The most direct environmental benefit will be in the form of greenhouse gas emission reductions (particularly CO_2), with all options combined projected to provide the potential for reductions of around thirty to over ninety-five million tons carbon dioxide by 2010 (implementation of the BAU to aggressive scenarios)[19]. Some options, though not all, lead to considerable criteria pollutant emission reductions with an overall potential for 390 thousand tons SOx and 440 thousand tons NOx avoided per year by 2010 with implementation of the aggressive scenarios. Water and soil quality can be somewhat improved, or at least not damaged, by implementing careful management

[19] The reductions for carbon dioxide were estimated with the impact of the combined BAU and aggressive scenarios if fully implemented. For each category, full chain emissions was compared to an fossil analog. The total carbon dioxide avoided (compared to a fossil option) for full implementation of biopower, biofuels and bioproducts was estimated for each scenario separately. The emissions were covered growing the biomass (e.g. fertilizer use); harvesting the biomass, transporting the biomass to the conversion site; and processing the biomass. Depending on the sector; downstream steps of the value chain were also included. The reader is referred to the full report for detailed discussion of the analysis for each sector.

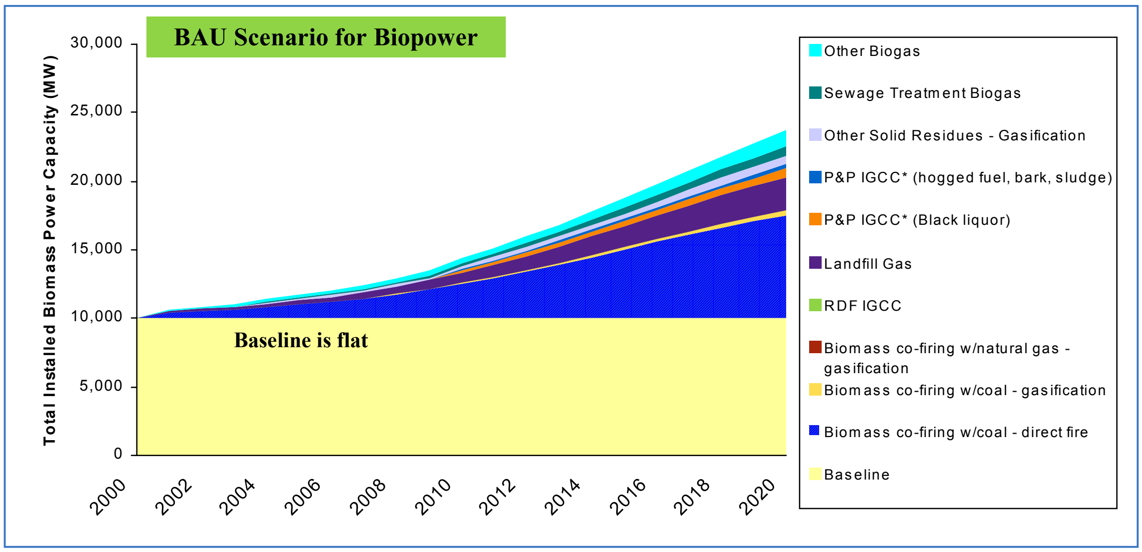
practices based on state-of-the-art technology. The U.S. government could play a key role in making sure that sound environmental technology is applied where appropriate in biomass projects.

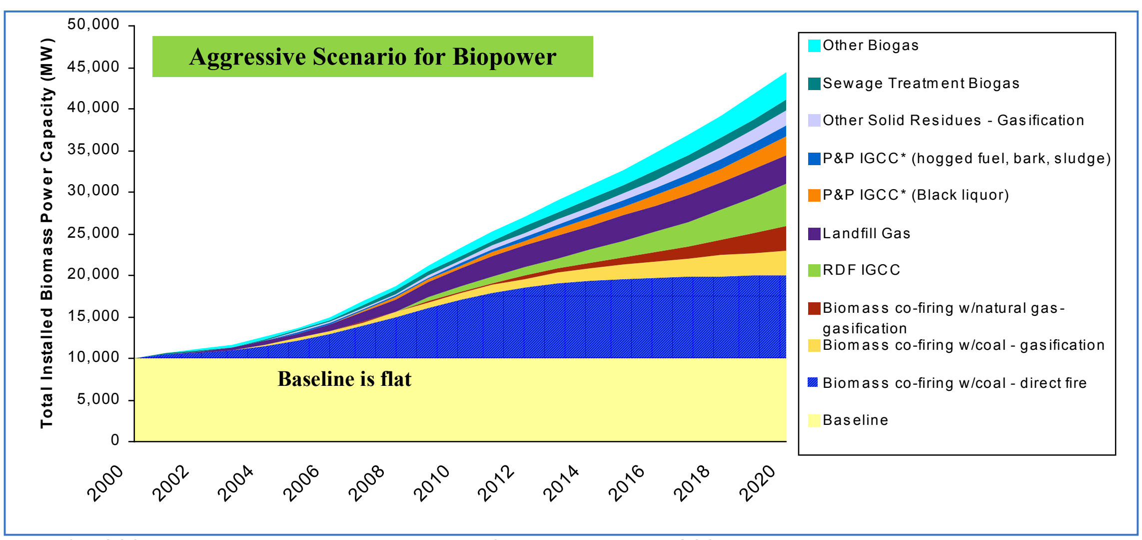
Biopower Scenario Analysis

Biopower Growth Potential

The baseline for biopower was taken as 10,000 MW capacity with zero growth in the baseline. The growth in capacity for biopower for the BAU and aggressive scenarios is shown in Figure 24 below:

Figure 24: Cumulative Growth in Biopower Capacity for BAU and Aggressive Scenarios





Note: P&P IGCC represents incremental capacity resulting from repowering with IGCC. Existing capacity included in baseline.
Source: Arthur D. Little analysis

Even in a BAU scenario, biopower is expected to grow, based on the implementation of some of the most attractive options, which requires only limited government support. Biomass co-firing and LFG/biogas represent most of the additional capacity in the BAU scenario. Biomass power achieves approximately 40% growth in capacity by 2010 (An additional 4,000 MW) and could more than double by 2020. For this scenario (as well as the aggressive scenario described below) the early establishment of a stable biomass supply infrastructure and market is important, especially for grid-based biopower options.

The Aggressive Growth scenario is based on the 2020 Vision for the biomass energy industry represented in Figure 22. In this scenario:

- Technology advances are rapid and lead to significant performance improvements and cost reductions. This requires investments in technology that are focused on winning technologies, that leverage the best resources, and that support a strong portfolio of options within each technology area.
- There is strong support from the public sector to level the playing field for biomass (via direct support and via state restructuring plans that include provisions for renewable energy). This action is focused on rapidly accomplishing market penetration of “low hanging” fruits (e.g. biomass co-firing with coal and landfill gas-based power options) through regulatory reform, and on targeted support and aggressive advocacy of high-risk / high-impact technologies such as biomass gasification.
- Market conditions and public opinion favor fuel diversity and green power. In this scenario the public is willing to pay a premium for green power and recognizes biomass as truly green power. This would require educational efforts and public awareness campaigns.

In the Aggressive Growth scenario, broader application of biomass technology and a more rapid market penetration of all technologies lead to greater impact by 2015. In this scenario, all technologies are introduced commercially by 2010 and successful development and demonstration of gasification technology is accomplished at that time. Capacity increases of 13,000 MW by 2010 are included in the Aggressive Growth scenario.

Other technologies are less important in the near-term but are important for sustained growth beyond 2010. The pulp & paper industry represents an important growth area after 2010 via repowering with IGCC (including black liquor gasification). Other industries that generate residues are expected to contribute modestly throughout the 2000-2020 timeframe. RDF could become a significant source of biopower in the long-term, provided technical and environmental issues are addressed successfully. Gasification for co-firing could become significant beyond 2010, in both coal- and natural gas-fired power plants.

Both of these scenarios would lead to significant environmental benefits, as well as benefits to the rural communities that would produce the biomass (primarily for co-firing). The benefit for the U.S. balance of payment would be minimal, as the biomass feedstock would principally offset coal-based power, which is produced from domestic coal resources.

Because of the cost-effectiveness of the early options, the cost of the BAU scenario is not as high as some of the other options (e.g. biofuels). Although the cost of implementing the aggressive scenario within the timeframe could be high, adopting a more gradual pace of development of the higher-risk technologies may reduce the cost, so that the cost of these technologies could be further reduced before they are introduced to the market.

Biopower Environmental Benefits

Compared with relevant competing technologies, biopower offers the greatest emissions benefits for CO_2, SO_2 and, in some cases, NO_x. In all cases CO_2 reductions (per kWh delivered) compared to coal and/or natural gas-fired gas turbine combined cycle (depending on the option) are significant, ranging from 65-100% over fossil fuel alternatives. As a result, greenhouse gas emissions are significantly reduced.

Except when compared to natural gas-fired gas turbine combined cycle (GTCC) technology, biomass power results in significant SO_2 reductions (80-97%) since biomass is generally much lower in sulfur than coal. In other processes (e.g. gasification) sulfur removal to very high levels is possible and often required for internal reasons.

NO_x benefits are more mixed, and generally are technology (versus fuel) dependent. Natural gas GTCC technology sets a very high standard for NO_x (low emission levels), which is also true for many biogas-fired options. Biomass co-firing with coal has the potential for significant NO_x benefits (e.g., 20% overall reduction for 10% co-firing on an energy basis). Reciprocating engines produce levels of NO_x comparable to or greater than the grid average unless special control equipment is used.

Emissions of non-methane hydrocarbons and carbon monoxide are generally unaffected by the use of biomass as a fuel. Methane emissions are generally reduced, especially in cases where coal-based and natural gas-based power generation is displaced (because of natural gas losses in production). These reductions further add to the greenhouse gas reduction benefits of biomass technology, in addition to the CO_2 reductions. Advanced biopower conversion technologies may produce particulate matter (PM) reductions. All technologies that convert biogas or landfill gas produce less PM than the grid average. Co-firing with coal biomass options does not produce significant PM reductions.

The solid waste and water effluent impacts are expected to be moderate and manageable. Most biomass is low in ash, and in most cases, the ash is non-toxic and can actually have value as fertilizer. However, due to the current regulations, sale and application of (partially) biomass-derived ash will require re-certification. Water effluents can contain suspended solids and biological oxygen demands but toxicity is not usually a serious concern.

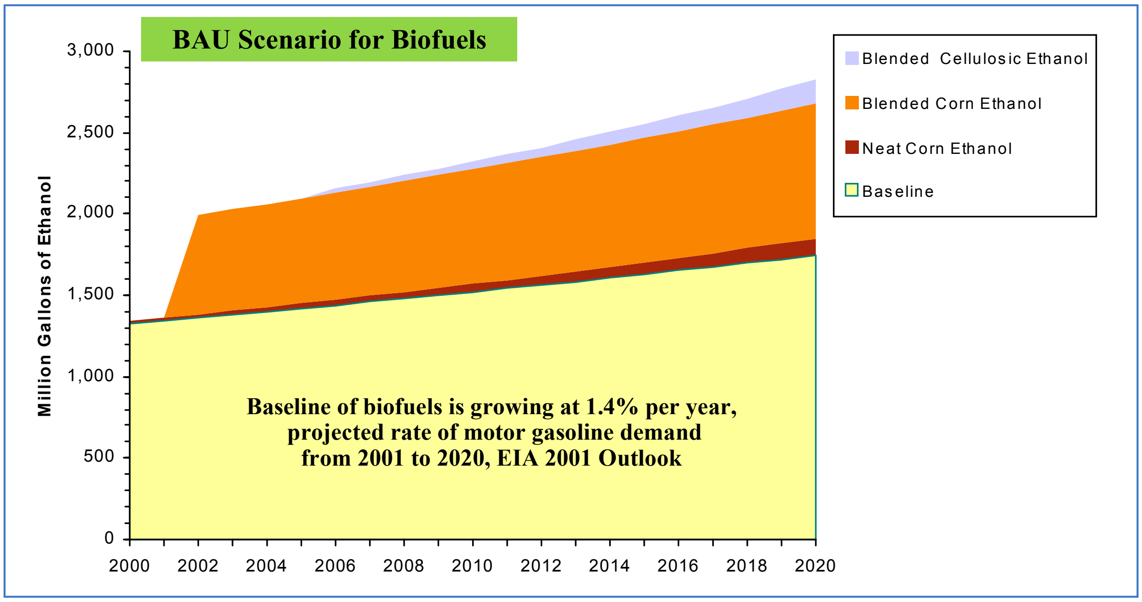
Finally, repowering existing facilities with advanced technology (e.g. black liquor gasification) could considerably reduce the environmental impact of existing biomass utilization facilities.

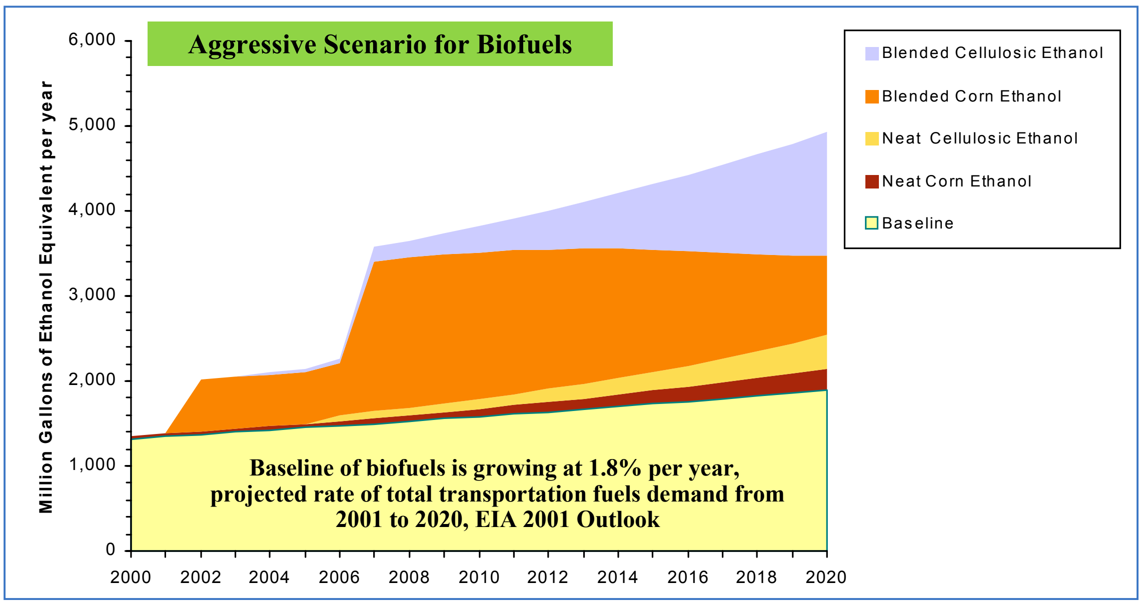
Biofuels Scenario Analysis

Biofuels Growth Potential

The baseline in 2000 for biofuel consumption was taken as 1324 million gallons of ethanol consumed for both the BAU and aggressive scenarios. The growth in consumption for biofuels for the BAU and aggressive scenarios is shown in Figure 25 below. The scenario increased consumption are cumulative; with each scenario baseline increasing also.

Figure 25: Cumulative Growth in Biofuels Consumption for BAU and Aggressive Scenarios





Note: The BAU Baseline is growing at 1.4% per year the projected rate of motor gasoline demand from 2001 to 2020, EIA 2001 Outlook. The Aggressive scenario baseline is growing at 1.8% per year, the projected rate of total transportation fuels demand from 2001 to 2020, EIA 2001 Outlook. The size of the near-term market for California (2003) depends upon unsettled requirements for oxygen content in California gasoline, nevertheless, current estimates place ethanol demand in the range of 580 million to 715 million gallons per year ethanol (or 37,834 barrels/day to 46,641 barrels/day ethanol). Additional requirements for RFG or oxygenated gasoline in rest of U.S. ~ 114,000 BD (1750 MM gal ethanol/y)

Source: Arthur D. Little analysis, COSTS AND BENEFITS OF A BIOMASS-TO-ETHANOL PRODUCTION INDUSTRY IN CALIFORNIA, COMMISSION REPORT, California Energy Commission, March 2001; SUPPLY AND COST OF ALTERNATIVES TO MTBE IN GASOLINE, TECHNICAL APPENDIXES, Technical Documents, California Energy Commission, 1998, prepared by Purvin & Gertz, Inc.

Even the BAU scenario projects a significant increase in the use of biofuels, as it projects a continuation of the ethanol tax credit as well as the reformulated gasoline (RFG) oxygenate requirement, combined by gradual reduction in ethanol production cost. An additional 800 million gallons of ethanol are produced in 2010 over the baseline of 1500 million gallons in the BAU scenario. Baseline growth in biofuels is 200-million gallon ethanol by 2010. Given the number of projects under study and the number of permits in application for new ethanol production capacity, this projection appears feasible, albeit highly dependent on crude oil prices.

An Aggressive Growth scenario for biofuels could be envisioned where ethanol would be universally used as an oxygenate additive and be broadly used as an octane enhancer. The Aggressive scenario has an additional 2300 million gallons of ethanol in 2010 over the baseline of 1600 million gallons. Baseline growth in biofuels is 300 million gallons ethanol by 2010. This would bring the total up to around 2% of gasoline used (on an energy basis) which is similar to gasoline renewable content standards currently being considered in both the U.S. and Europe. This could have considerable impact due to the huge market potential, provided there is:

- Strong regulatory support for bioderived oxygenates for RFG nationwide (such as tax credits, subsidies, or content standards)
- Successful technology development and cost reduction
- Highly developed solutions for integration with conventional blending and distribution terminals
- Continued and stable incentives for biofuel production

The market penetration of biofuels is likely to be strongly influenced by developments in technology production cost, government incentives, and conventional fuel prices. While the absolute magnitude in the increase of ethanol use could be tremendous, the cost associated with achieving such growth would be high: the magnitude of the existing tax credit is almost equivalent to the feedstock cost for corn-based ethanol production. Clearly, such levels of government support are hardly considered in biopower or bioproducts

Biofuels Environmental Benefits

The environmental benefit of biofuels can be considerable. Biofuels offer the least costly option to virtually eliminate CO_2 emissions from transportation fuel chains, which would ultimately become necessary if significant reductions of greenhouse gas emissions were to become necessary.

The benefits in criteria pollutant emissions are a bit more difficult to understand. When used as an oxygenate in RFG, ethanol could play a critical role in criteria pollutant emissions reduction: the very reason for the RFG mandate in the first place. Ongoing debate and research will more clearly define the actual benefits of the oxygenate requirement in RFG over the next few years.

Without legislative protection, the clean fuels benefit of biofuels may be modest, as automotive original equipment manufacturers (OEMs) tend to be able to trade-off emissions versus power or cost in re-optimization of engines while still meeting the relevant emission standard.

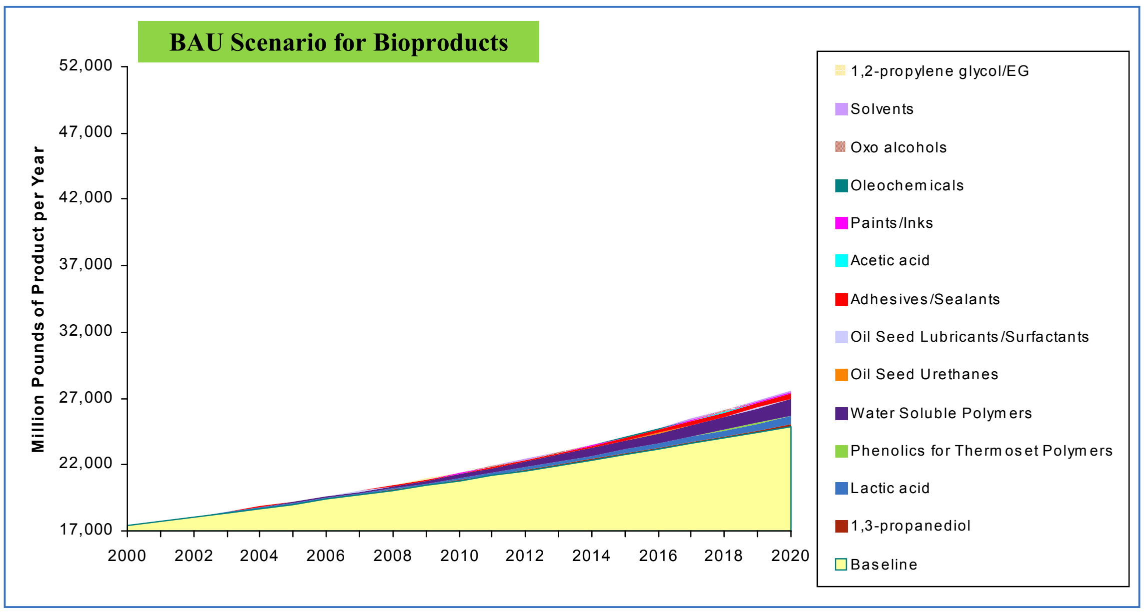
The MTBE debate in California indicates that ethanol might provide a non-toxic biodegradable oxygenate blend stock. In instances where leaking storage tanks could occur, such leaks would pose a lower risk of toxicity to the drinking water. Of course, addressing the root-cause of the contamination (e.g. leaking storage tanks) will also reduce the risk of contamination of ground water with any fuel used.

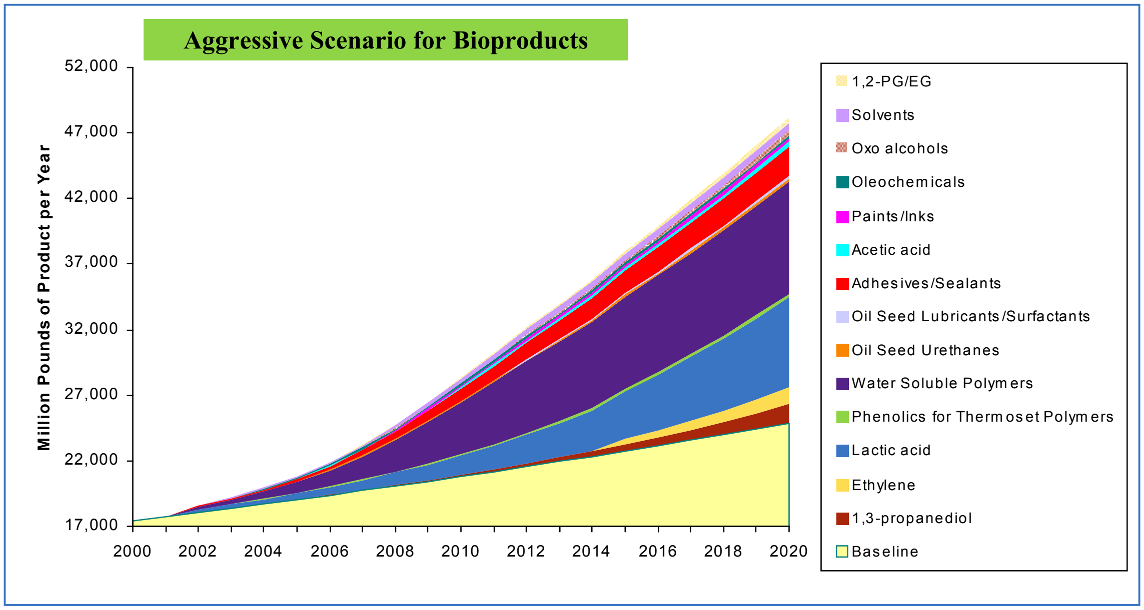
Bioproducts Scenario Analysis

Bioproducts Growth Potential

The baseline in 2000 for bioproduct consumption was taken as 17400 million pounds (8.7 million tons) for both the BAU and aggressive scenarios. The growth in consumption for bioproducts for the BAU and aggressive scenarios is shown in Figure 26 below. The scenario increased consumption are cumulative; with each scenario baseline increasing also.

Figure 26: Cumulative Growth in Bioproducts Consumption for BAU and Aggressive Scenarios





Note: The BAU and Aggressive Scenario baselines are growing at 1.8% per year, projected rate of total transportation fuels demand from 2001 to 2020, EIA 2001 Outlook

Source: Arthur D. Little analysis, COSTS AND BENEFITS OF A BIOMASS-TO-ETHANOL PRODUCTION INDUSTRY IN CALIFORNIA, COMMISSION REPORT, California Energy Commission, March 2001; SUPPLY AND COST OF ALTERNATIVES TO MTBE IN GASOLINE, TECHNICAL APPENDIXES, Technical Documents, California Energy Commission, 1998, prepared by Purvin & Gertz, Inc.

In the BAU scenario, bioproducts would capture a small fraction of the growth volume of specific chemicals markets. This would lead to production of an additional 600 million pounds of bioproducts over the 8.7 million-ton baseline in 2010. The baseline growth of bioproducts from economic growth is projected at 3400 million pounds by 2010 for both the BAU and Aggressive scenarios. Despite relatively attractive fundamental economics, compared with fuels and power, bioproduct growth is modest in a BAU scenario:

- No current large-scale incentives for bioproduct use (such as tax credits for ethanol fuel, green power and other renewable power credits)
- Most of the growth in the BAU scenario for bioproducts comes from traditional bioproduct growth (e.g. starches) and from products produced by physical extraction (e.g. seed oils). Bioproducts already have a high market share in these markets and the markets are relatively mature
- Limited potential market for low-hanging fruit
- Technologies with greater potential impact do not reach the market until much later and will penetrate the market slowly

Even in the BAU scenario, however, we expect bioproducts to have a considerable impact in the longer term, as we expect that eventually competitive economics will be achieved for broad-based application of bioproducts to polymers and solvents. However, this would happen long after 2010; outside the narrow scope of this study.

With aggressive technology and market development and some government support (but not necessarily product price support), a significant impact (even tripling) may be achievable by 2020. Technologies with high impact potential (such as fermentation-based polymers and monomers) would become commercially available in the 2010 timeframe, but with plant construction and market penetration inertia, significant market penetration would not be achievable before 2020. If similar incentives were applied as are currently available for ethanol, considerable increases in a number of currently marginal bioproduct applications could be achieved.

Given the modest absolute size of product markets (as compared with fuels and power markets) the relative potential impact of bioproducts on greenhouse gas emissions and rural economic development can be considerable, but not large in absolute terms. Because of the more limited scale of production, at least early facilities may well be integrated into existing chemical plants or into existing corn or paper mills. However, the economic attractiveness of bioproducts and the market appeal of, for example, green plastics, along with the experience that could be gained with early applications of advanced fermentation technologies, could well aid the development of biofuel and biopower options. The projected economics of a wide range of bioproducts are expected to become competitive with conventional products so that they will not require continued government price or product support (e.g. subsidy, tax credit). Nevertheless, government support for technology development is a critical component in achieving projected economic competitiveness for bioproducts.

Bioproducts Environmental Benefits

Bioproducts can offer significant benefits, on a relative basis, but their modest potential markets do not support enough volume for a high absolute level of impact. Because biomass-derived products can be durable (e.g. they are not necessarily incinerated as their end disposition), their production also counts as a form of carbon sequestration. Greenhouse gas emission reductions of bioproducts could offer significant benefits but the absolute amount is somewhat limited by the size of chemical markets.

Criteria pollutant emissions are not strongly impacted by the implementation of bioproducts. Criteria pollutant emissions are most strongly affected by the amount of fuel that must be burned to produce the products (e.g. furnace or boiler fuel for process heating) and the amount of energy required is comparable to that for conventional petroleum-based products. This particular analysis presents a conservative case in that extensive process integration that will reduce onsite fossil fuel requirements and/or grid electricity requirements was not addressed due to lack of data on the processes.

The solid waste and water effluent impacts are expected to be moderate and manageable and similar to that for ethanol production by fermentation. Most biomass is low in ash and in most cases the ash is non-toxic. Fermentation based processes are likely to generate solid wastes from spent cell mass which can either be used as fuel internally or disposed. Untreated water effluents can contain suspended solids and biological oxygen demands but toxicity is not usually a serious concern. However, availability of water, particularly for fermentation-based processes, may be a concern in arid and semi-arid regions. In the case of gasification coupled with Fischer-Tropsch synthesis, water is formed as a by-product that could be used for irrigation purposes after treatment.

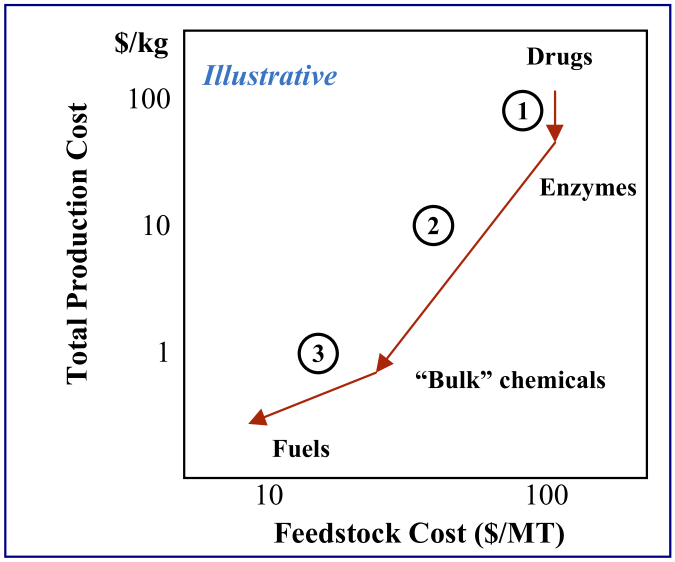
Barriers to Rapid Growth of Biomass-Based Energy & Products

Technology Development Needs

To exercise the options for growth, further technology development is necessary. In fact, it is central to broadening the appeal of biomass-derived energy and products, and thus to achieving significant increases in their use. Key factors include (See also Figure 27):

- Scale-up of existing processes to improve the economy of scale of bioconversion processes and to bring it on par with that of competing petroleum-based processes (Figure 27, step 1).
- Development of conversion technologies that achieve higher yield of conversion, especially where relatively expensive feedstocks are used. However, experience teaches that improved efficiency of the process also reduces overall capital and operating costs, since in the conversion of biomass a large fraction of each component is required to process the incoming biomass. Examples of such developments include the development of black liquor gasification (instead of direct combustion), and the development of more efficient and integrated cellulosic bioethanol technology (Figure 27 step 2).
- Production and use of lower cost feedstocks. Further reduction in the biomass production cost would considerably enhance the economics of most options (and this becomes more critical as the cost and performance of the conversion technology are improved). Higher yield production, but also more efficient co-production of co-products for energy and product use with production of foods and feeds are needed. In addition, the conversion technologies must be able to use these lower cost feedstocks, which is often more challenging (Figure 27 step 3).
- Demonstration of reliability and safety of biomass production processes (e.g. black liquor gasification).

Figure 27: Example of Cost Reduction Trajectory for Application of Biomass Fermentation Technology to Different Product Markets



Source: Arthur D. Little analysis

However, time and resources are needed for these technology developments and for commercialization; both of which are often underestimated. The time required for technology development is expected to considerably limit the rate of implementation of biobased products, for example:

- Technology development for industrial conversion processes from pilot to full commercial scale typically takes about three to five years for very successful development. Five more years should be added for successful bench-scale development.
- Especially for chemical and derivative products (e.g. polymers), additional development time will be required for application and market development.
- Market penetration following market introduction typically takes twenty to forty years for capital-intensive processes such as fuels or power production, slightly less for chemicals and for products that experience market pull. Market penetration in less than ten years is very rare, and mostly limited to situations of extreme urgency, none of which appear likely to apply to biobased energy and products (potentially with the exception of ethanol use as an MTBE replacement in California).

Altogether, this means that considerable effort and resources must be dedicated to the development of biomass technologies if even the most mature and competitive technologies are to have significant impact by 2010. In order not to delay the overall process, technology, product, and market developments must take place in parallel. The government can help guide, coordinate and support this process, which will require collaboration of a number of industries not previously accustomed to working together.

External Uncertainties

A number of external factors will likely affect the development of biomass-derived energy and resources in the United States. While the biomass development community specifically, and even the U.S. government have only limited control over these factors, it is critically important to understand them, to ensure that policies developed are robust against these uncertainties, mitigate against them where necessary, and take advantage of them where possible.

Conventional energy and feedstock prices are a significant factor in determining the prices of competing conventional energy and products, as well as feedstock costs for biomass-derived alternatives:

- Developments in crude oil prices are likely to have considerable impact on all options, particularly on the fuels and products options, which are competing directly with petroleum-based products.
- Gasoline shortages in 2000 and 2001 due in part to localized rulemaking, leading to boutique fuel requirements, provide an opportunity for biofuels.
- Uncertainty in natural gas and electric power prices also could have a significant impact on bioenergy viability, particularly for biopower options.
- Fluctuations in farm product prices could impact the cost of biomass feedstocks for energy and products production. However, there is potential for some degree of stabilization of prices from the farmers' perspective.

These fluctuations in prices cause uncertainty for investors in biomass plant and production, which add risk in moving forward aggressively with the development of biomass projects.

Political factors also directly impact the market demand and support environment for biomass-derived energy and products:

- The situation around reformulated gasoline oxygenates (MTBE) is unresolved and though it currently appears favorable for biofuels, other outcomes are still possible, including a relaxation of the oxygenate requirement. This could result in either a strong rise or a significant drop in the demand for and value of ethanol.
- The political support for tax incentives for biofuels has been rather stable over the past fifteen years, but they are subject to political decision on a reoccurring basis.
- Discontinuation of PURPA support for biopower plants has caused concern over long-term reliability of government support for biomass-derived power.

Swings in public opinion of course influence the political process, but can also impact biomass options directly:

- Public environmental concern drives much of the interest in biomass-derived energy and products. While some biopower options are perceived "green" (e.g. landfill gas), others may not be (e.g. co-firing biomass in coal plants). Similar issues apply to fuels and chemicals.

- Until recently, use of genetically modified-crops for non-human food uses was considered uncontroversial in the United States, but experience with genetically modified-corn cross-fertilization has called this into question. This could have significant ramifications for the feasibility of certain crop improvement efforts for energy and product applications.
- NIMBY (Not in my backyard) concerns for waste-to-energy facilities might affect RDF biopower options.
- Impact of biomass production/collection/transport on the local environment may be a concern.

However, in some of these categories (less likely the first and last), the United States government can play a very positive role in creating a more stable environment for the investment in biomass-derived energy and product projects.

Challenges to Process Integration: Biorefineries

One way to reduce the uncertainty in individual biomass projects is to integrate them into "bio-refineries": combined production facilities that produce a mix of biomass-derived energy and chemical products, possibly combining biomass with other feedstocks. Combining biomass-derived processes into such "bio-refineries" can offer two potential primary benefits:

- Maximizing the value of the products per ton of feedstock (for combining biomass-derived processes only)
- Maximizing the economy of scale of the overall process (for combining biomass-derived with fossil-based processes)

Current corn mills (wet and dry) and some pulp & paper mills are good examples of "bio-refineries", and it is likely that new biomass-derived energy and production will be integrated with them where feasible, to benefit from the economy of scale and infrastructure already in place. Greenfield "bio-refineries" could also provide similar benefits ultimately, but require careful consideration. Two principal types can be distinguished:

- "Bio-refineries" that do not involve any synergy between the production processes may be attractive in some cases where they offer economy of scale. The benefit of doing so will likely be limited; but where it exists, they will likely be implemented readily, subject to the usual project risk trade-off. This type of "bio-refinery" could well include conventional feedstocks as well as biomass feedstocks.
- "Bio-refineries" that do offer direct synergy between the production processes offer greater potential benefit, but are also more complex and are not well-understood. Given the inter linking of the production processes inherent in their development, the risk will be greater initially, and investors may be hesitant to invest in "bio-

refineries" based on a combination of first-of-a-kind processes. Thus their development will likely be more important in the post-2010 timeframe.

The U.S. government could further support the study of such synergistic bio-refineries, but should focus on realistic options.

Policy Options

Although several attractive options have been identified to increase significantly the use of biomass-derived energy and products, significant hurdles must yet be overcome. There are several reasons why the government should play a central role in helping to overcome these barriers:

- Many of the benefits of increased biomass use for energy and products represent a “common good” (e.g. environmental protection, improvement of the United States balance of payments, development of the rural economy).
- Implementation of several of the options would require a change in the use of pubic land (e.g. CRP lands).
- Timeframes and risks associated with investments are often not consistent with criteria for independent industrial support of the technologies, and require some risk sharing by the government.
- Several of the options will require the establishment of new markets or infrastructures, which will require some form of government regulation.
- Several options require the collaboration of industries not accustomed to working with each other, which could be catalyzed by the government.

Thus government policy support is critical in the further development of the use of biomass to produce energy and products. To better understand which policy options are most attractive, it is critical to have a good overview of these barriers, a summary of which is provided in Figure 28.

Figure 28: Overview of Barriers to Implementation of Biomass Options

	Fundamental Technology Barrier	Cost not Acceptable	Address Early Adopter Markets	Poorly educated consumer	Regulatory Barriers
Biopower	• Gas cleaning for BIGCC must be improved • Design & eng. guidelines for co-firing implementation don't exist	• Cost of stand alone biopower is too high	• Black liquor gasifiers face market conservatism	• Biopower not seen as really green • RDF / Waste-to-energy seen as an "incinerator"	• Fly-ash regs for co-firing are restricting • Deregulation uncertainty • Biomass feedstock markets not well developed • New Source Review
Biofuels	• Organisms for CBP ethanol not robust • Gas cleaning for Bio-FT not adequate	• Cost of all options more than 1-2 times as expensive for fuel value of products	• Oxygenate markets prove difficult to substitute ethanol (market, infrastructure issues)	• Value of green fuels not recognized	• Ethanol credit only extend to all renewable fuels? • Limitations on GMO R&D and production
Bioproducts	• Fermentation-based commodity-scale production not well developed • Large-scale reactor technology not developed	• Cost of current technologies may still be too high for early adopter applications	• Need early markets for fermentation-based feeds	• U.S. consumer not very responsive to green branding • Competition with "biodegradable" fossil derived products	• Product standards for new chemicals not yet established • Limitations on GMO R&D and production
Biomass Feedstock	• Recalcitrance of cellulosic biomass for applications other than power	• Biomass low energy density makes transportation costs key issue • Harvesting, yield	• Pulp & paper expand power production • Ag residues for more revenue for farmer	• Biomass equated with MSW; "garbage" • Biomass utilization plants perceived as "dirty"	• Markets for biomass not well developed • Competition among biomass forms (ag wastes vs energy crops)

A large number of different policy instruments have been developed in the United States and abroad, which could be applied to stimulate and support the growth of biomass-derived energy and products. These instruments could be categorized into ten key categories, as shown in Figure 29. This figure also provides an overview of how well each of these options might address the key barriers, based on U.S. and international experience.

Figure 29: Effectiveness of Policy Support Instruments by Type

Option Category	Absolute Cost	Typical Cost-Effectiveness	Effectiveness in Addressing Key Barriers				
			Fundamental Technology Barrier	Cost not Acceptable	Address Early Adopters	Poorly educated consumer	Regulatory Barriers
R&D Support	$	+++	+++	+	-	-	+
Direct subsidies	$$$$$	---	-	+++	+	-	-
Risk Sharing	$$$	++	+	++	++	-	-
Demonstration Projects	$$	+	-	-	++	-	-
Benchmarking / Best Practice	$	++	-	+	-	-	-
Voluntary Agreements	$$	++	+++	+	+++	+	+++
Standards / (de-) regulation	$	+++	+	+	++	-	+++
Infrastructure Investments	$$$$	+/-	-	+	+	-	-
Tax Measures	$$$	++	++	+++	++	-	-
Information Provision	$	+++	-	-	+	+++	-

Breakthrough Energy Technologies for Industry, Phase II Report, for Nederlandse Organizatie Voor Energie en Milieu. Arthur D. Little 1997.

From our analysis of all the options available against the barriers biomass is facing, we concluded that the growth of biomass use for energy and products would be most effectively aided by:

- Sustained and carefully targeted R&D support to achieve the necessary improvements in technology performance and cost
- Voluntary agreements and public/private partnerships to efficiently marshal and integrate resources from a variety of organizations necessary for efficient large-scale development and implementation
- Tax measures to entice early adopters and/or bridge the cost-competitiveness gap for selected biomass options
- Information programs and consumer education programs to generate public support and enable the development of premium markets for green energy and products based on biomass
- Support for crop production or support for crop price stability
- Direct support for biomass-based energy and products. Such programs could include subsidies, price management or buy-down programs to achieve the aggressive goal in all sectors by 2015 or 2020. A different implementation of such control instruments is the use of renewable content standards for power and fuels. While on

the one hand they are quite prescriptive, on the other they leave it up to the market to find the lowest cost of implementation, and thus distributes the cost of implementation over industry and consumers via market mechanisms. Even if such support must be sustained, its cost may be partially offset on a regional basis by increased tax revenues associated with increased domestic or regional production.

Of course this analysis must be weighed against the overall policy of the administration and the feasibility with the current regulatory and political environment. The level of support required to achieve a significant impact (such as doubling or tripling biomass use) must not be underestimated.

Conclusions

Overall, the possibilities for biomass-derived energy and products are considerable. However, they are not achieved without cost. In the near term, and with modest additional cost, considerable impact can be achieved by focusing on a number of attractive options. In the longer term significant impact can be achieved with the further development of some higher-risk technologies. This impact takes the form of reductions in greenhouse gases and other pollutants, increased domestic production of sustainable crops and utilization of agricultural and industrial residues consumed in the United States, and increased high-value economic activity in rural areas.

Achieving a doubling or tripling of use of biomass energy and products is possible by 2015 or 2020, but will come with even higher cost than the more gradual implementation described above. Nevertheless, the development of new production and conversion technologies and the application to new markets could enable this increase nationwide, and in each of the biomass use categories (power, fuel, and products).

However, we recommend that the United States government carefully weigh the rate of increase in the use of biomass-derived energy and products against the cost. We believe that attempting to achieve rapid doubling of biomass energy and products use at all cost (e.g. by 2015) will lead to the application of technologies that could be superseded by superior and more cost-effective technologies only a few years later. Thus, we believe that a somewhat more long-term view of the biomass opportunity which allows for the development of technologies that could become commercial in the 2010-2020 timeframe, would be beneficial, and may lead to a more optimal use of resources for the benefit of the nation.

Appendix to Summary Prose Report

Abbreviations and Definitions

Agricultural residues	Crop waste typically left on the field or used in various applications includes corn stover, wheat straw, sugar bagasse, rice straw
BAU	Business as usual
BIGCC	Biomass integrated gasification-combined cycle
Biogas	Gaseous biomass formed via aerobic or anaerobic digestion of biomass wastes, includes landfill gas, digester gas, sewage gas
EIA	United States Energy Information Administration
Energy crops	Crops purposefully grown for their energy content; examples include switchgrass, hybrid poplar, and willow
ETBE	Ethyl tertiary butyl ether
FT-Diesel	Diesel made using Fischer-Tropsch chemistry using syngas as a feedstock
GJ	Gigajoule (10^9 joules)
GMO	Genetically modified organism
GTCC	Gas turbine combined cycle
IGCC	Integrated gasification combined cycle
kWh	Kilowatt-hour
LFG	Landfill gas
Million BTU	10^6 BTUs (British thermal units)
MSW	Municipal solid waste
MTBE	Methyl tertiary butyl ether
MW	Megawatt, 10^6 watts
NIMBY	"Not in my backyard"
NOx	Nitrogen oxides, e.g. NO, NO_2
OEM	Original equipment manufacturers
PM	Particulate matter
PURPA	Public Utility Regulatory Policy Act
R&D/D	Research and development and demonstration
RBEP	Regional Biomass Energy Program
RDF	Refuse derived fuel
SOx	Sulfur oxides, e.g. SO_2
SSF	Simultaneous saccharification co-fermentation technology to make ethanol from cellulosic materials
Syngas (Synthesis gas)	Mixture primarily of hydrogen and carbon monoxide
USDOE	United States Department of Energy
WTE	Waste-to-energy

Summary of Resource Available Data

Figure 30: Cumulative Available Biomass Resources (Million Dry Tons per Year) With a Farm-Gate Price of 0 to $40/dry ton

	Agricultural Crop Residues	Forest Residues	Primary Mill Residues	Other Wastes	Biogas	Sludge	Potential Energy Crops
Southeast	14.4	34.3	1.0	45.1	3.3	15.2	59.9
Northwest	3.2	9.7	0.1	7.2	0.4	2.4	1.3
West	47.0	8.1	0.2	47.8	3.6	17.4	49.4
Northeast	2.3	6.6	0.3	26.6	0.9	3.4	5.6
Great Lakes	89.1	25.1	0.2	34.6	3.2	12.1	42.5

Note: Regions defined by Regional Biomass Energy Program: Great Lakes region: MN, IA, WI, IL, IN, OH and MI; Northeast: New England, NY, PA, NJ, and DE; Northwest: WA, OR, ID, and MT; Southeast: MD, WV, VA, NC, SC, GA, FL, AL, MS, LA, AR, MO, KY, TN; West: CA, NV, WY, ND, SD, NE, KN, OK, TX, NM, CO, UT, AR; Data did not include Hawaii and Alaska

Source: Arthur D. Little analysis based on existing resource assessment studies

The supply curve data is shown below. Amounts are in million dry tons per year versus farm-gate price in dollars per dry ton.

Figure 31: Data from Available Biomass Supply Curve for the United States: Farm Gate Price Versus Resource Amount in Million Dry Tons per Year

	Farm gate price, $/dry ton, transportation & processing not included										
	0	10	20	30	40	50	60	70	80	90	100
in MM tons/year											
Agricultural Crop Residues	0.0	0.0	3.2	138.8	155.9	157.5	157.6	157.9	158.0	158.0	158.0
Forest Residues	0.0	0.0	0.0	19.2	83.7	104.5	110.4	117.7	121.6	123.1	123.4
Primary Mill Residues	0.0	0.0	0.3	1.8							
Wastes	123.6	161.4									
Bio Gas	11.3										
Sludge	50.5										
Energy Crops	0.0	0.0	0.0	59.1	158.7	212.1					

Source: Arthur D. Little analysis based on existing resource assessment studies

In general the data processed by ADL agrees well with a recent ORNL resource analysis[20].

Figure 32: Comparison of ADL Resource Assessment with ORNL Resource Analysis

	US Available Quantity at 0-40 $/dt (farm-gate price), million dt/year		
Biomass Type	**ADL Analysis**	**ORNL[6] Analysis**	**Comments**
Agricultural Crop Residues[1]	156	151	Both analyses used the same source for corn stover and wheat straw. The ADL analysis included rice straw and cotton stalks.
Forest Residues	84	45	Both analyses used the same source. The ADL analysis used updated data.
Primary Mill Residues	2	90	Both used the same source. ORNL data included the currently used portion (for fuelwood, fiber, and misc. by-products).
Other Wastes[2]	161	37	ORNL included used and unused fractions of MSW wood, yard trimmings, and C&D wood. The ADL analysis included only unused fractions of organic MSW, C&D wood, and UTR.
Biogas[3]	11	NA	
Sludge[4]	50	NA	
Potential Energy Crops[5]	159	188	Both used same source. ADL analysis assumed a linear interpolation of the ORNL data.
Total	**623**	**511**	

[20] Based on a presentation given by Marie Walsh of ORNL (Walsh, 2000). Transportation cost assumed to be $10/dt to convert the ORNL data

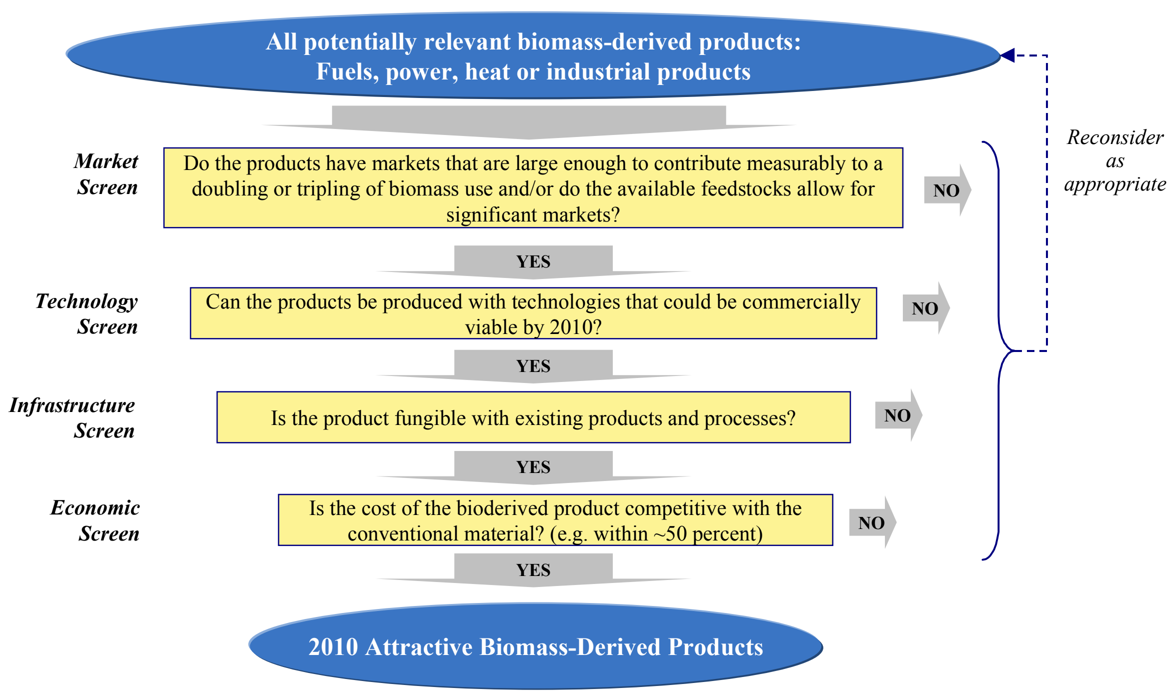
Source: Arthur D. Little analysis based on existing resource assessment studies;

1. Agricultural crop residues include corn stover, wheat straw, rice straw, and cotton stalks.
2. Other wastes include the organic fraction of municipal solid waste, urban tree residues, and construction and demolition wood.
3. Biogas includes landfill gas, digester gas, and sewage gas.
4. Sludge includes manure and bio-solids.
5. Potential energy crops include switchgrass, hybrid poplar, and willow.
6. Based on a presentation given by Marie Walsh of ORNL (Walsh, 2000). Transportation cost assumed to be $10/dt to convert the ORNL data

Summary of Technology Screening Analysis

Figure 33 summarizes the screening methodology used in the analysis of biomass-derived power, fuels, and industrial products. The screening analysis was done in parallel for each category.

Figure 33: Summary of Screening Methodology Used in Biomass Study



The options identified for biopower are summarized in Figure 34.

Figure 34: Options Identified for Biopower Analysis

Technology		Grid Power					Onsite Power & CHP				
		Conventional Biomass*	Municipal Solid Waste (MSW	Refuse Derived Fuel (RDF)	Sewage Sludge	Biogas - Landfill gas	Biogas - Sewage Treatment	P&P - Black Liquor	P&P - Hogged Fuel & Bark	Other Solid Biomass Residues	Biogas - Other Residues
Direct Combustion (solid biomass)	Biomass-only Rankine Cycle	X	X	X	X			X	X	X	
	Cofiring Rankine Cycle (coal)	X									
	Biomass-only Direct-Fired GT									X	
	Biomass-only Heat Only		X	X	X			X	X	X	
Gasification (solid biomass)	Biomass-only Rankine Cycle	X		X	X					X	
	Biomass-only GT/IGCC	X		X	X			X	X	X	
	Biomass-only ICE				X					X	
	Biomass-only Fuel Cell	X		X	X					X	
	Cofiring (coal or NG Rankine, IGCC, GTCC)	X		X	X						
Liquefaction (solid biomass)	Biomass-only Pyrolysis (Rankine, GT, ICE)	X		X	X				X	X	
	Cofiring with oil (Rankine, GT, ICE)	X		X	X				X	X	
Direct Combustion (gaseous biomass)	Biomass-only Rankine Cycle					X	X				X
	Cofiring Rankine Cycle (with natural gas)					X	X				X
	Biomass-only GT, GTCC, ICE					X	X				X
	Cofiring GT, GTCC, ICE (with natural gas)					X	X				X
	Biomass-only Fuel Cell					X	X				X
	Cofiring Fuel Cell (with natural gas)					X	X				X

The options that were screened from further detailed analysis are summarized in Figure 35.

Figure 35: Options Removed from Biopower Screening Analysis

Biopower Screening Analysis Results: Technologies Removed			
Market	**Technology**	**Infrastructure**	**Economics**
• Biomass-only direct-fired gas turbine • All biogas-natural gas cofiring technologies • Biomass/coal co-gasification for IGCC cofiring • Biomass gasification cofiring with natural gas Rankine • Biomass only heat only	• Utility-scale liquefaction technologies/ applications • Liquefaction/ cofiring opportunities • Gasification/fuel cell applications • Direct combustion of gaseous biomass in Rankine cycles and GTCCs for onsite power	• None were removed	• Direct combustion of solid biomass in a Rankine cycle for grid power, onsite power and CHP • Gasification of conventional biomass* for grid power applications • Gasification of sewage sludge for grid power applications • Liquefaction of other solid biomass residues* for onsite power applications using Rankine, GT, and ICE

The options identified for biofuels are summarized in Figure 36.

Figure 36: Options Identified for Biofuel Analysis

Technology		Pure Fuel					Blending Agent				
		Starch/Sugar Crops	Cellulosics	Municipal Solid Waste (MSW	Other Wastes	Seed Oils & Greases	Starch/Sugar Crops	Cellulosics	Municipal Solid Waste (MSW	Other Wastes	Seed Oils& Greases
Fermentation	Corn Ethanol (or other sugar feed stocks)	X					X				
	Cellulosic Ethanol from TVA process		X	X				X	X		
	Simultaneous saccharification (SSF) & co-fermentation;		X	X	X			X	X	X	
	Consolidated bio-processing		X	X	X			X	X	X	
	Syngas fermentation		X	X	X			X	X	X	
	Algal hydrogen production				X						
Pyrolysis & Thermal Treatment	Thermal pyrolysis oils		X	X	X			X	X	X	
	HTU oils		X	X	X			X	X	X	
C1 Chemistry	Gasification and hydrogen synthesis	X	X	X	X						
	Gasification and synthetic natural gas synthesis	X	X	X	X						
	Gasification and methanol synthesis	X	X	X	X		X	X	X	X	
	Gasification and dimethyl ether synthesis	X	X	X	X						
	Gasification and dimethoxymethane synthesis	X	X	X	X		X	X	X	X	
	Gasification and Fischer-Tropsch diesel synthesis	X	X	X	X		X	X	X	X	
	Gasification and Fischer-Tropsch Gasoline synthesis	X	X	X	X		X	X	X	X	
	Gasification and MTG synthesis	X	X	X	X		X	X	X	X	
	Gasification and Mixed Alcohol Synthesis	X	X	X	X		X	X	X	X	
Low Temperature Processing	Methyl esters(Biodiesel) from seed oils & greases				X	X				X	X

Note: "Cellulosics" is used generically to describe cellulose-rich dedicated energy feed stocks that are amenable to each biomass-conversion technologies (poplar, switchgrass, homogeneous agricultural wastes etc.); TVA is the Tennessee Valley Authority process; MTG is methanol to gasoline process

The options that were screened from further detailed analysis are summarized in Figure 37.

Figure 37: Options Removed from the Biofuel Screening Analysis

Biofuel Screening Analysis Results: Technologies Removed			
Market	**Technology**	**Infrastructure**	**Economics**
• None were removed	• Processing of MSW by SSF technology for pure fuels & blending agents • Ethanol via consolidated bio-processing • Ethanol via fermentation of syngas • Algal hydrogen production • HTU and Pyrolysis oil fuels • Options involving the gasification of MSW • Gasification and mixed alcohol synthesis for pure fuels & fuel blending agents • Gasification & DMM synthesis for pure and blended fuels • The use of waste greases and other animal fats for biodiesel as a fuel or a fuel blending agent • Fuel cell vehicles for any fuel other than hydrogen, methanol, ethanol, FT-diesel or gasoline	• Hydrogen transportation options • Fischer-Tropsch gasoline • MTG-gasoline • Methanol • DME • Biodiesel from seed oils • Synthetic natural gas for fuel cell vehicles • Synthetic natural gas for ICEs	• Fischer-Tropsch diesel

The options identified for bioproducts are summarized in Figure 38.

Figure 38: Options Identified for Bioproduct Analysis

Currently Used as Primarily Food By-products	• Acetic acid • Amino acids • Ascorbic acid • Citric acid • Ethanol • Fumaric acid	• Gluconic acid • Glutamic acid • Itaconic acid • Lactic acid • Mannite • Propionic acid	• Sorbit • Sterols • Vanillin • Vitamin E • Xylitol • Xanthan gum		
Commodity Chemicals	• Acetates • Acetic acid • Acetone • Acrylic acid and esters • Adipic acid	• N-Butanol • 1,4- Butane diol • Butadiene • BTX • Bisphenol A replacement	• Carbon black /activated carbon • Ethanol • Ethylene • Ethylene glycol • Lipids (Fatty acids/alcohols)	• Formaldehyde • Isopropanol • Methanol • Naphtha • Pentanes/Pentenes • Phenol	• 1,2-Propane diol • Propylene • Syngas • Tetrahydrofuran
Polymers & Fibers	• CAB • Cellulose • Cellulose acetates • Cellulose ethers • Cellophane	• Epoxidized soybean oil • Nitrocellulose • Polyethylenes • Polyhydroxy Alkanoates	• Polylactic acid polymers • Polypropylenes • Rayon • Starch-based polymers • Other functionalized seed oils		
Specialties	• Acetol • Acetaldehyde • Anthraquinone • Gamma butyl lactone • Catechol	• DALA • DMSO • Erythritol • Furfural • Furfuryl alcohol • Glycerol/glycerin	• Lactic acid • Lactic esters • Levulinic acid • Levoglucosan • Methyl-THF • Nonyl phenol • Propionic acid	• 1,3-propane diol • Lipid-based lubricants • Resorcinol • Rosins and rosin esters • Sugar esters	• Succinic acid • Terpenes • Vegetable oils for hydraulic fluids, engine oils, penetrating oils, & cutting fluids

The options that were screened from further detailed analysis are summarized in Figure 39.

Figure 39: Options Removed from the Bioproduct Screening Analysis

Bioproduct Screening Analysis Results: Product/Technologies Removed				
Market		Technology	Infrastructure	Economics
• Fumaric acid • Carbon black/activated carbon • Low density polyethylene (LDPE) • Resorcinol • Ethyl acetate • Butyl acetates • Propionic acid • Nonyl phenol • n-Butanol • Isopropyl alcohol • Furfural • Acetic anhydride • Methanol • Cellulose acetate tow • Glycerol • Rayon • Cellulose ethers • Cellulose acetate flake • Terpenes • Sorbit	• Cellophane • Citric acid • Itaconic acid • CAB • Nitrocellulose • Succinic acid • Lactic acid • Xanthan gum • Cellulose acetate for fibers • DMSO • Gluconic acid • Rosin acid/esters • Anthraquinone • Natural rubber • Catechol replacement • Polyhydroxy Alkanoates • Furfuryl alcohol • Cellulose in insulation • Sugar esters • Acetaldehyde • Acetol • Starch-based polymers	• Acrylic acid/esters from lactic acid • 1,2-propylene glycol from lactic acid • Ethylene from ethanol (and its derivatives) • Succinic acid and its derivatives • Propylene from bioderived isopropanol (and propylene's derivatives) • Formaldehyde from pyrolysis products • Pentanes/pentene from pyrolysis products • Levoglucosan from pyrolysis products • Acetic acid from pyrolysis products • Bisphenol-A replacements from pyrolysis products • Butadiene from pyrolysis products • BTX from pyrolysis products • Levulinic acid (and its derivatives)	• Acetic acid • Acetone • Ethanol for chemicals • Seed Oil based polymers • Levoglucosan • Levulinic acid • Plant based lubricants • Syngas as product	• Naphtha from FT synthesis from gasification of biomass • Sugar feed stocks for fermentation derived from high temperature pyrolysis technology (e.g. levoglucosan)

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